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QUARTERLY PROGRESS REPORT NO. 7

Contract No. AF 19(122)-7, Items II & III

June 1, 1953 to August 31, 1953

Item II: Reliability Research
Item III: Coding Circuitry

Prepared by

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Submitted for the staff by

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RELIABILITY RESEARCH AND CODING CIRCUITRY

ABSTRACT

This report summarizes the work performed under the "Reliability Research" and "Coding Circuitry" items of the contract during the period from May 16, 1953 through August 15, 1953. These items are primarily concerned with improving the reliability of a specific future IFF system.

Progress made in the implementation of a mock-up of the transmission links of the IFF system is described. This includes discussions of a pulse-train correlator, an optimum i-f filter, and other associated apparatus. Consideration is given to problems associated with the use of pulse-train correlators at the airplane. Quantitative results are given on the beginning of a series of analyses being made to study the performance of pulse-train correlation systems in the presence of Gaussian noise. Treatment is given to further speculations on the use of noise for the challenge and reply signals. The use of marginal-checking procedures in the evaluation of the reliability of a transistorized flip-flop circuit, and new developments in the supporting transistor-testing program are discussed.

a. Personnel and Administration

1. Martin W. Essigmann, Coordinator (two-fifths time Item II, one-fifth time Item III, engineer)
2. Sze-Hou Chang (half time Item II, engineer)
3. George E. Pihl (one-fifth time Item II, one-tenth time Item III, engineer, to June 12, 1953)
4. John S. Rochefort, liaison man (full time Item II, engineer, from May 16, 1953)
5. Harold L. Stubbs (half time Item II, mathematician)
6. Walter H. Lob (full time Item II, physicist)
7. Thomas P. Cheatham, Jr. (one-fourth time Item II, engineer)
8. Louis J. Nardone (full time Item III, engineer)
9. Myron L. Bovarnick (one-fourth time Item II, engineer, to June 1, 1953)
10. Jacob Wiren (half time Item II, engineer)
11. Anthony Briana (full time Item II, engineer)
12. John J. Klein (half time Item III, engineer, from June 15, 1953 through July 17, 1953; and from August 3, 1953)
13. Thomas J. White (full time Item II, cooperative student assistant, through June 19, 1953; full time Item II, engineer, from June 22, 1953)
14. Walter F. Goddard (two-fifths time Item II, one-fifth time Item III, technician)
15. Mary D. Reynolds (two-fifths time Item II, one-fifth time Item III, secretary)
16. Lawrence J. O'Connor (full time Item II, cooperative student assistant, through July 31, 1953; part-time student assistant Item III from August 10, 1953)
17. Charles U. Knowles (part-time student assistant Item III through July 17, 1953; full time Item III, cooperative student assistant, from July 20, 1953)
18. Robert H. Lawson (part-time student assistant Item III through July 17, 1953; full time Item II, cooperative student assistant, from August 3, 1953)

George E. Pihl resigned from his position as an Associate Professor of Electrical Engineering at the University, effective June 12, 1953, to undertake employment in industry. He had served continuously on a half-time basis with the research group assigned to work under this contract since its beginning.

Thomas J. White, a cooperative student assistant on work under this contract until his graduation in June, was appointed a Research Assistant effective as of June 22, 1953.

Martin W. Essigmann was promoted from Associate Professor of Electrical Engineering to Professor of Research in Communications, effective July 1, 1953.

Walter H. Lob was promoted from Research Associate to Assistant Professor of Research in Communications, effective July 1, 1953.

b. Communications

1. Correspondence

Listings of all non-expendable property received for use under this contract have been sent to the Research Accountable Property Officer under the dates of May 30, 1953, June 30, 1953 and July 31, 1953. A consolidated listing of all such property was submitted on June 9, 1953, after a complete inventory had been taken.

2. Conferences

June 2, 1953. Visit received from R. W. Wagner, the project engineer for Item III, of AFCRC. Work under Item III as reported in Quarterly Progress Report No. 6 was discussed.

June 10, 1953. Conference at Northeastern University among R. Wagner, C. Ryan, and R. Bradbury of AFCRC, and the staff at Northeastern concerned with work under Item III. The purpose of this conference was to discuss proposed work directed toward (1) the evaluation and expansion in scope of the present transistor-testing procedures, and (2) the quantitative determination of the reliability of a transistorized storage cell of a different type than that previously studied.

June 25, 1953. Conference at Northeastern University among E. Samson, C. Hobbs, and W. Bishop of AFCRC, and the staff at Northeastern concerned with work under Item II. The purpose of this conference was to inform the Northeastern staff of new operational specifications for the IFF coding procedure, and to discuss the work reported in Quarterly Progress Report No. 6. Special consideration was given to the new approach to the ground-to-air jamming problem as described in that report.

June 26, 1953. Visit received from B. Bodenheimer, 2nd Lt. USAF of the USAF Auditor General's Office. Lt. Bodenheimer made a spot check of the accountable property at Northeastern, and reviewed the system of property control maintained at Northeastern.

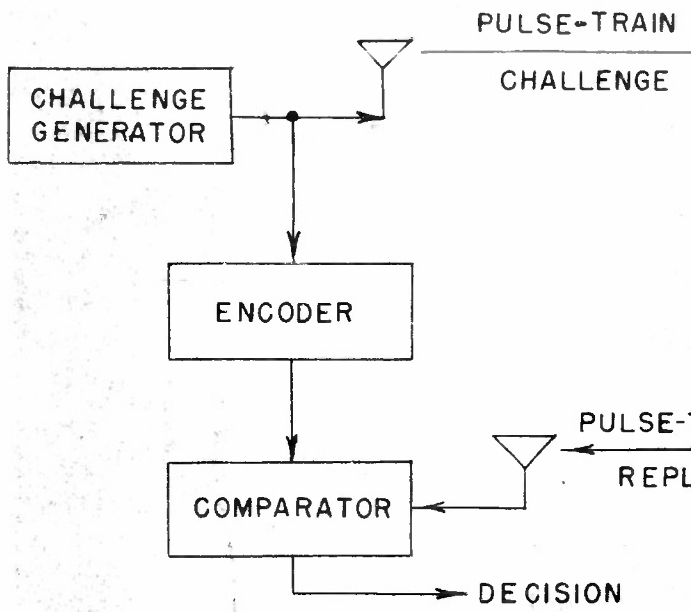
July 28, 1953. T. P. Cheatham, Jr. and S. H. Chang attended an informal conference at AFCRC among persons interested in IFF and related problems. Problems of mutual interest were discussed, with Dr. Cheatham taking an active part in the discussion.

August 14, 1953. J. J. Klein and C. H. Knowles visited R. Bradbury at AFCRC to compare certain aspects of the transistor-testing programs at Northeastern and AFCRC.

c. Statement of the Problem

Item II of the contract is concerned with research directed toward the specification of a high-reliability system for use in the ground-to-air and air-to-ground links of a specified IFF system. This system is one in which the challenge as generated by the interrogator is an n-digit binary number, and an encoder at the airborne transpondor provides an r-digit reply. The reply, on reception at the responsor on the ground, is compared with a locally encoded version to determine whether or not it is correct.

The block diagram below shows the essential features of the IFF system for



which methods of improving transmission reliability are being studied. The two transmission links in the system differ in that the correct reply is available at the terminal of the air-to-ground link, whereas a priori knowledge of the challenge is not available at the transpondor. Atmospherics, enemy noise and pulse jamming, and enemy attempts at interrogation are being considered as factors which need to be combatted in obtaining high transmission reliability. The IFF system is assumed to be secure against an enemy who can only listen; hence, the aspect of cryptographic security introduced by the presence of two encoders in the system is not part of the present problem.

Item III on coding circuitry involves in general the design, construction, testing, and evaluation of reliable circuits for use in the final IFF system. The circuit being studied at present is a transistorized bistable device of particular design for use in the shift register involved in the encoder unit of the system. A supporting unit of work under this item is a transistor-testing program.

d. Methods of Attack

System Reliability

The work in progress under the Item II phase of the contract comes under the classification of system reliability. This term refers to the performance of the system under the condition that all equipment operates perfectly. Primary attention is being given to the use of pulses as the signal in the two transmission links; however, for the sake of completeness some consideration is being given to other forms of signal such as noise.

General Considerations

The air-to-ground link of the specified system is inherently capable of being made more reliable than the ground-to-air link, since a priori knowledge of the correct reply is available. This fact makes possible the use of cross-correlation techniques in the reception of the coded reply. Figure 1 of the Appendix shows a block diagram of a test setup which can be considered to be a mock-up of this transmission link. All of the circuit work of this period has been devoted to the construction of equipment shown by the blocks of this diagram.

The section to the right of the adder represents the responsor receiver section. It includes an optimum filter designed to optimize the pulse amplitude in the presence of noise jamming, and a pulse-train correlator designed to select the correct pulse train in the presence of pulse jamming. The section to the left of the adder simulates the transmission link. Provision is made for the generation of coded r-f pulse trains (signal-generator branch), and the simulation of pulse jamming and two types of noise jamming.

From the standpoint of error detection and threshold setting for correlation detection, it is desirable that the total transmitted energy be constant from one challenge, or reply, to the next. This could be accomplished by a variety of means, such as: (1) letting the pulse used to represent a digit have two possible positions - one position to represent a one and the other to represent a zero; (2) shifting the phase of the carrier by 180 degrees to differentiate between a one and a zero; (3) using a two-frequency FM system - thus the discriminator output would represent a one by + 1 and a zero by - 1; or (4) transmitting ones and zeros and restricting the pulse trains used in the n-digit system to those which contain the same number of ones. Consequently, although no particular scheme has yet been settled upon for maintaining constant energy from one pulse train to the next, the final system will employ some scheme to accomplish this purpose. Method (4) will be employed in the mock-up system merely because it can easily be accomplished with existing equipment.

With one exception, the mock-up system could be used to represent the ground-to-air link. In this case, however, the existing pulse-train correlator could not be used since a priori knowledge of the challenge would not be available. Consequently, unless a completely directional communication system were employed (this scheme has been discussed in past reports and is considered unfeasible at the present time because of the antenna development problem) the best that could be hoped for would be the improvement in the presence of noise jamming obtainable with the optimum filter. The ground-to-air link would be completely vulnerable to a type of pulse-jamming which resembled a correct challenge.

In the event of pulse jamming of this type (as was pointed out in the previous report), the best policy would be to turn off the ground-station interrogator and allow the jamming signal to serve as the challenge. Thus the process of identification would be accomplished at the ground station by merely comparing its coded version of the enemy signal with the reply transmitted by the airplane undergoing identification.

This identification process could be accomplished with presently contemplated equipment if a single airplane and a single jammer were located on the same azimuth. If a larger number of planes were present, the ground equipment would become complicated to the extent that a separate antenna would be required to receive the jamming "challenge" from a jammer that was not located on the same azimuth as the plane undergoing identification, memory units would be required in order to store the respective replies from a number of planes located along the same azimuth until the "challenge" arrived, a computer would be required to calculate range data in order to identify the replies from a number of planes, and a jamming analyzer might very well be needed in order to determine when to use "enemy challenge" and how to use it most effectively. Consequently, although the utilization of the "enemy challenge" would go a long way toward making the IFF system invulnerable to enemy jamming, the required ground-station equipment could very well become formidable.

Recognizing the low reliability obtainable in the ground-to-air transmission link in the presence of jamming, theoretical effort during this report period has been given to improving the performance of this transmission path. The deeper realization that the optimum filter in the North sense for the detection of pulse trains in noise is a pulse-train correlator has resulted in considerable attention being given to the theoretical aspects of correlation. This study has resulted in a potential system which makes use of correlation techniques in the airplane, and employs a correlator with a simple threshold device.

Preliminary results of the correlator study are covered in a subsequent section entitled, "Analyses of the Performance of Hypothetical Pulse-Train Correlation Systems in the Presence of Gaussian Noise". In the beginning it has been necessary to somewhat idealize the operation of the correlator and make certain approximations and assumptions which may prove to be impractical in the final model. Therefore, it will probably be necessary to refine the calculations and supplement them by experiments in order to check their applicability to the new system introduced below.

The first and second progress reports of this series gave attention to the problem of optimum detection of the signals received at the airplane. It was tacitly assumed that cross-correlation would provide the optimum means of detection, and this would require storage of the correct challenge at the airplane. Calculations were made to show that punched tape could provide a practical solution to the mechanization of such a scheme. The scheme was not pursued further due to the operational difficulties entailed in the distribution and control of the tapes. It is expected that equivalent transmission reliability will be obtained, however, if all possible challenges are stored at the airplane, the transmitted challenge is repeated a number of times, and each challenge upon arrival at the airplane is cross-correlated against all stored challenges - the stored challenge showing maximum correlation over a number of tries being chosen as the one that was transmitted. In subsequent sections of this report, consideration is given to such a system in which the pulse-train challenge is stored by means of weighting networks attached to the taps on a delay line. Since the challenge has n digits, 2^n weighting networks and decision devices are required if maximum reliability is to be obtained. In this treatment, attention is first given to a suggested practical system, and a qualitative operational analysis is included to indicate its expected performance in the presence of various types of interference. A supporting analysis attempts to show quantitatively the degree of reliability improvement that may be expected from such a scheme in the presence of

Gaussian-noise interference. In this analysis, again, the system has been idealized to what is probably an impractical extent in order to permit the evaluation to be made.

All of the schemes referred to in the above, and discussed in detail in later sections, make use of integration over successive repetitions of the same challenge in order to obtain improvement in reliability. The numerical analyses have been made on systems wherein this integration has been performed on a digital basis - i.e. by the method commonly called binary integration. It has been shown by Harrington[1] that while this method is slightly poorer in principle than the analogue method, the non-ideal characteristics (such as finite memory) of the analogue integrator make the two about equivalent in the final analysis. An important advantage gained by the use of binary integration stems from its allowing the use of pulse circuitry instead of the less stable linear circuitry demanded by the analogue method. The types of circuits required are those for which reliable transistorized versions are either presently available, or seem possible.

For the sake of completeness and in order to ensure that no alternate system is being overlooked, some time has been devoted to the use of noise as the transmission signal. Recent progress is discussed in a subsequent section.

Mock-up System

During this report period, work on the mock-up system has been mainly devoted to construction and testing of some of the units indicated in Fig. 1. Due to the nature of the work, progress will be briefly mentioned here and elaborated on in more detail under e. Apparatus and Equipment.

Testing of the pulse modulator described in the previous report showed it to be inadequate for use from the standpoint of carrier feed-through. Consequently the modulator was redesigned along the ringing-circuit principle and was tested entirely satisfactory. Two such units have been constructed - one for use as a signal-pulse modulator, and the other for use as a jamming-pulse modulator.

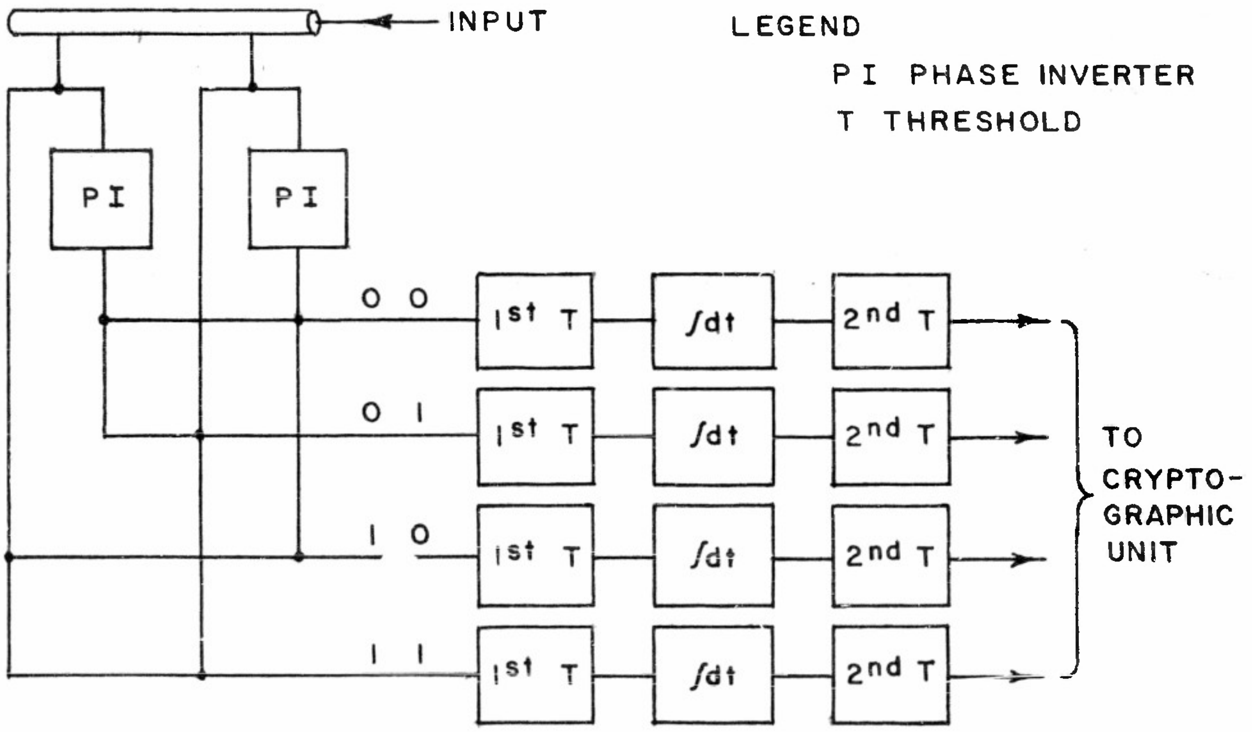
The jamming-pulse generator was originally designed so that periodic pulses would be obtained from its output. A new pulse generator under development at the present time will provide jamming pulses which are randomly spaced in time.

A prototype optimum filter for use in the i-f band has been constructed. The filter is matched for use with a carrier pulse 0.6 μs in duration and a frequency of about 30 mc. At the present time the filter is working qualitatively but not quantitatively. Further work on the unit awaits the construction of a probe for use in the 30-mc band.

During this report period the overall operation of the laboratory model of the pulse-train correlator has been improved by redesign of the switching circuitry to remove certain undesirable loading effects. The device also has been simplified and made more reliable by a redesign of the d-c amplifier section. These changes are described in greater detail under e. Apparatus and Equipment.

The Repeated-Challenge System

Outline of the System. It is generally recognized that in the absence of storage in the airplane the ground-to-air link of an IFF system is more vulnerable than the air-to-ground link, due to the fact that the correct challenge is not available at the airplane, whereas the correct reply is available at the ground station. A system has now been worked out which is believed to remove this weakness of the ground-to-air link by transmitting the same n-digit challenge repeatedly (perhaps fifty times) and with random timing before a reply is elicited. The challenges are received in the airplane, detected, and fed to a delay line with n taps, feeding n phase inverters. 2^n Adding-busses are connected to the taps (directly and via the phase-inverters) in such a way that each adding-bus corresponds to one of the 2^n possible different challenges. (The sketch shows this for n = 2)



Those outputs of adding-busses which exceed a certain value (first threshold) are time-integrated over the interval between synchronizing (perhaps radar) pulses, whose spacings are randomised within certain limits. Upon reception of a synchronizing pulse, those integrators whose voltages exceed a (second) threshold value cause the cryptographic unit to produce the corresponding replies, which are then transmitted in turn in rapid succession (interlaced?). At the same time the integrators are cleared, and a time-gate prevents any further synchronizing pulses from affecting the unit for a length of time equal to the minimum interval between synchronizing pulses. The first threshold may be set such that at maximum range a challenge will almost certainly cause its adding-bus voltage to exceed the threshold. The second threshold is set so that under the same transmission conditions a string of identical challenges will cause the proper integrator voltage to exceed the threshold.

Philosophy

In this section the repeated-challenge system will be considered in greater detail, and reasons for its various features will be given. It is easily seen that the additions in the adding-busses and the time integrations in the integrators will result in very good cancellation of random noise and random pulse jamming, so that the attention in this section is focused on the operation of the system in the presence of planned enemy interference.

In accordance with the design of the pulse-train correlator*, the spacings of the pulses of each challenge will be staggered according to a fixed scheme to avoid multiple coincidences of pulses and taps prior to and subsequent to the instant of exact superposition.

The spacing between successive challenges is to be randomized within limits, in order that periodic pulse jamming cannot be employed to jam the same digit in each challenge. It is realized, on the other hand, that a jammer might achieve this result by sending out a jam pulse as soon as he receives the first pulse of a challenge. It is necessary, however, for this jam pulse to arrive at the target plane while the same challenge is still being received, that the difference in transmission times from the ground station to the target plane (1) via the jammer, and (2) directly, must be less than the duration of the challenge. For a challenge of reasonable size this method of jamming would therefore be effective only for a limited region and with the jammer located such as to be quite vulnerable to elimination.

The number of digits per challenge (n) is expected not to exceed six. It is felt that, with proper miniaturization, sixty-four adding-busses and associated circuits can be accommodated in the airborne unit. If, for reasons of cryptographic security, longer challenges are deemed necessary, a way could presumably be found to break the challenges up into four- to six-digit groups and to treat each group individually, thus making the size of the equipment increase linearly with the number of digits instead of exponentially.

The first threshold has the purpose of keeping the integrators from responding to anything but a correctly lined-up challenge. In the absence of such a threshold, each incoming pulse would yield a certain contribution to an integrator, and different challenges with the same number of pulses would not be differentiated between.

In the absence of enemy interrogation (and if only one ground station is received by the plane) only one integrator voltage will increase to more than the second threshold. In this case, then, only one reply will be triggered off by the arrival of the synchronizing pulse, and accurate range information can be obtained at the ground station from the round-trip transmission time. An enemy who attempts to upset the system by barrage interrogation will find that, to exceed the second threshold, each interrogation will have to be sent a great number (perhaps 50) of times within one synchronizing period. There will then

* See Quarterly Progress Report No. 2.

not be time enough within that period to send many (say more than 5) different interrogations, each that many times. The transpondor then will reply to these enemy interrogations and to the friendly challenge, one after the other. Since, among others, it has produced the correct reply, the airplane will still be regarded as a friend (especially after several rounds). Since, however, the reply to the friendly challenge is not necessarily the first one to be sent upon arrival of the synchronizing pulse, somewhat different round-trip times will result for successive rounds, in other words, the accuracy of the obtainable range information is reduced by enemy interrogation.

In the event the enemy duplicates the synchronizing pulse the transpondor will be triggered by the enemy's pulse at least some of the time. Due to the time-gate in the synchronizing-pulse receiver, the replies will not be sent at an excessive rate, so that enough time still is available for the friendly challenges to integrate and exceed the second threshold. Due to the random timing of the friendly synchronizing pulses, no consistent range information will be obtained from the replies due to the enemy's synchronizing pulse. The replies due to the friendly synchronizing pulses can therefore be recognized by the relative constancy of the round-trip time.

A limiter at the input to the delay line can be provided to prevent strong individual pulses (at close range from the ground station, or due to powerful jamming) from exceeding the first threshold.

Analyses of the Performance of Hypothetical Pulse-Train Correlation Systems in the Presence of Gaussian Noise

System for application at the ground. Consider the block diagram of Fig. 2. It is assumed that the input to the correlator is connected to the output of the i-f amplifier of the IFF responsor and that the signal being received is immersed in Gaussian noise and consists of a train of pulses properly coded to correspond to the switch positions of the correlator. In this system a sinusoidal carrier is shifted 180 degrees to differentiate between the ones and zeros of the binary code. The bandwidth of the i-f amplifier is assumed to provide an appropriate match to the pulse width of a code symbol, i.e. the signal is assumed to reach its peak amplitude during the time of the pulse. The pulse recurrence period is sufficiently long for the given i-f bandwidth that independent samples of noise can be assumed during adjacent pulse periods, and the digit and space lengths are equal.

For a case covered by the above assumptions, Rice[2] has shown that the envelope distribution density of the output voltage of the i-f amplifier can be given by

$$p(R) = \frac{R}{\psi_o} \exp\left[-\frac{R^2 + P^2}{2\psi_o}\right] I_o\left(\frac{RP}{\psi_o}\right) \qquad (1)$$

where

R = envelope amplitude

P = peak value of the sinusoidal signal

ψ_o = noise power at the output of the amplifier.

$I_0\left(\frac{RP}{\psi_0}\right)$ = value of the modified Bessel function of the first kind and order zero for argument $\frac{RP}{\psi_0}$.

Assuming an ideal correlator for an n-place code, the envelope probability density of the adding-bus voltage V_Σ can be written as

$$p(R) = \frac{R}{n\psi_0} \exp\left[-\frac{R^2 + n^2P^2}{2n\psi_0}\right] I_0\left(\frac{RP}{\psi_0}\right) \tag{2}$$

and the corresponding probability distribution P(R) is p(R)dR. A more convenient form for future use is obtained if the following normalized parameters are introduced:

$$v = \frac{R}{\sqrt{n\psi_0}} \qquad a = \frac{\sqrt{n}\,P}{\sqrt{\psi_0}} = \sqrt{n}\,\rho$$ where ρ is the input signal-to-noise ratio.

$$\text{Thus, } p(R)dR = v\,dv \exp\left[-\frac{v^2 + a^2}{2}\right] I_0(av) \tag{3}$$

The blocking oscillator produces one pulse when the voltage V_Σ exceeds the threshold voltage V_T. It is assumed that the specifications on the system are such that this can happen only once during a digit, or during the space between digits.

The probability of the blocking oscillator producing a pulse due to signal and noise during the signal period is

$$P_S = \int_{V_T}^{\infty} p(R)dR = \int_{V}^{\infty} v\,dv \exp\left[-\frac{v^2 + a^2}{2}\right] I_0(av) \tag{4}$$

$$\text{where } V = \frac{V_T}{\sqrt{n\psi_0}}$$

and due to noise alone during the space period,

$$P_N = \int_{V}^{\infty} v\,dv \exp\left[-\frac{v^2}{2}\right] = \varepsilon^{-\frac{V^2}{2}}. \tag{5}$$

Equation (5) has been obtained from (4) by noting that when the signal is zero, $a = 0$.

Optimum reliability, in one sense, is obtained if the threshold voltage is adjusted to a value that minimizes the probability of error. For this system, errors are produced when the signal amplitude is interfered with by the noise so that the threshold is not reached (called a "miss"), and when the noise during the space periods is sufficient to exceed the threshold (called a "false alarm"). Letting the probability of a miss be represented by P_M, and noting that the false-alarm probability is the P_N previously defined, then the problem becomes one of determining the value of V_T that makes $(P_N + P_M)$ a minimum.

Harrington[1*] has shown that equations (4) and (5) can be combined to eliminate v and yield

$$P_S = 1 - \varepsilon^{-\frac{a^2}{2}} \int_{P_N}^{1} I_0(a\sqrt{-2 \log p})dp. \qquad (6)$$

By using a series expansion for I_0, it can be shown that

$$P_S = 1 - \varepsilon^{-\frac{a^2}{2}} \sum_{n=0}^{\infty} \frac{1}{n!} \lambda_n \left(\frac{a^2}{2}\right)^n$$

$$\text{where } \lambda_n = [1 - \sum_{k=0}^{\infty} \frac{1}{k!} P_N(-\log P_N)^k] \qquad (7)$$

$$\text{and } P_N = \varepsilon^{-\frac{V^2}{2}}.$$

Note that

$$P_M = 1 - P_S$$

* Much of the following is based upon background obtained in studying this reference.

so that $2P_e$, the probability* of error, is

$$2P_e = 1 - P_S + P_N. \tag{8}$$

Figure 3 shows plots of P_M and P_N vs V (the normalized threshold voltage) for a = 1 and a = 2. Figure 4 shows curves of $2P_e$ vs. V obtained by using eq. 8 and the data plotted in Fig. 3. For a 16-digit correlator, the curves for a = 1 and a = 2 correspond to input signal-to-noise ratios of 1/4 and 1/2, respectively. Inspection of the curves indicates that, for a = 1, the optimum value of V is 1.5; and for a = 2, it is 1.75. The corresponding figures for the error probabilities are given in the table below.

a	P_N	P_M	P_e
1	.33	.51	.42
2	.22	.30	.26

In addition to serving to fix the value of V_T, the results of the preceding analysis can be interpreted to provide a quantitative figure for the reliability improvement resulting from the use of the pulse-train correlator. For example, if $\rho = 1$, then the average probability of error values give the relative improvement gained by using a four-place correlator. Likewise, for $\rho = 1/2$, the same figures give the improvement gained by using sixteen places compared to four places.

In the system assumed for this analysis (see Fig. 2), the challenges and replies are repeated m times in rapid succession, and binary integration used following the threshold device to provide further improvement in reliability. The final decision as to whether or not the correct reply has been received is based upon whether or not a threshold count k is exceeded in the m trials. Here two new error probabilities can be defined. The first is a "miss" probability P_m which increases with k; and the second, a false-alarm probability P_n due to noise during the space intervals that increases with a decrease in k. It is desired, therefore, to find the value of the threshold count that minimizes $(P_m + P_n)$.

The probability P_S is the probability of a correct pulse train being registered at the counter. The probability of obtaining a count of x due to correct pulse trains (in a set of m repetitions of the same reply) is given

* It should be mentioned that P_e is not a true probability in the statistical sense, but an arbitrary function (i.e. half the sum) of two probabilities derived from two different sets. As such, in the following the term average probability will be used to represent P_e.

by the binomial distribution $C_x^m P_S^x (1 - P_S)^{m-x}$, and the probability of obtaining a counter reading of k or more, by

$$P_s = \sum_k^m C_x^m P_S^x (1 - P_S)^{m-x} . \tag{9}$$

This expression can be readily handled, as shown by Harrington, if the Edgeworth series approximation to the binomial distribution is employed. This gives

$$P_s = 1 - \phi^{(-1)}(Y) - \frac{a_3}{3!} \phi^{(2)}(Y) + \frac{a_4 - 3}{4!} \phi^{(3)}(Y) + \frac{10}{6!} a_3^2 \phi^{(5)}(Y) \cdots \tag{10}$$

where $Y = \dfrac{k - \bar{k} - 1/2}{\sigma}$

$\bar{k} = m P_s$ $\qquad$ $\phi(y) = \dfrac{1}{\sqrt{2\pi}} \epsilon^{-\frac{y^2}{2}}$

$\sigma = \sqrt{\bar{k}(1 - P_s)}$ $\qquad$ $\phi^{(-1)}(Y) = \displaystyle\int_{-\infty}^{Y} \phi(y)dy$

$a_3 = \dfrac{1 - 2P_s}{\sigma}$ $\qquad$ $\phi^{(n)}(Y) = \dfrac{d^n}{dy^n} \phi(y) \Big|_{y = Y}$

$(a_4 = 3) = \dfrac{6P_s^2 - 6P_s + 1}{\sigma^2}$

In a similar way, the probability P_n of obtaining a counter reading of k or more due to noise can be computed by using P_N in place of P_S. The miss probability P_m is evidently $1 - P_s$, and the problem resolves itself to one of plotting P_n and P_m vs. k, and determining the value k which makes $(P_n + P_m)$ a minimum.

The curves of Fig. 5 show results of such plotting for the case of $a = 2$, $m = 25$, V_T at optimum value. The curve of average error probability need not be plotted in this case, since it is evident from the steepness and curvature of the curves that the minimum point will occur practically at the intersection point where $k = 11.7$* and each of the error probabilities has a value of 0.00085. The average probability of error P_e, then, is also 0.00085.

* In practice, k would be made equal to either the nearest integer or the nearest power of two, depending upon the type of binary counter.

This figure is correspondingly reduced with an increase in m; however, computational difficulties arise in attempting a quantitative analysis for large values of m due to the need for the use of more terms in the Edgeworth series.

The equation for the probability density of the envelope of V_Σ (eq. 2) used in the above analysis is only applicable when no detector is used ahead of the correlator. For the more practical system, where a detector is desirable due to difficulty in cutting the lengths of delay line, a new formula is required. Equation 1 is still applicable for the voltage at the output of a linear detector of the envelope-tracer type, and the problem becomes one of finding the probability density of the sum of n random variables each having the probability density p(R) given by eq. 1. This can be readily accomplished through the use of the characteristic function of p(R), $\psi(s)$, since

$$\mathcal{F}[p(V_\Sigma)] = [\psi(s)]^n \tag{11}$$

and $p(V_\Sigma)$ is, then, the "n"th convolution of p(R) with itself, or, for n = 4,

$$p(V_\Sigma) = p(R) * p(R) * p(R) * p(R) \tag{12}$$

Because of the forms of the functions making up the right-hand side of eq. 1, the solution of the resulting integrals is not easy. The next section will describe a graphical technique which may be applied to effect the required result.

The pulse-train signal assumed in the above analysis used a 180-degree phase shift to indicate the difference between ones and zeros. In a more practical system, a dual-frequency transmission system would be employed, so that a frequency p would be used to represent a one, and a frequency q for a zero, and the detector would take the form of a frequency discriminator. The equation for the envelope probability density required in this case in place of eq. 1 is given by Rice[2] as

$$p(R) = R \int_{r=0}^{\infty} r\, J_0(Rr)\, [J_0(Pr)]^2 \exp\left[\frac{-\psi_0 r^2}{2}\right] dr. \tag{13}$$

<u>System for application at the airplane</u>. The block diagram of Fig. 6 shows the components which may be used in a transponder receiver in the airplane if pulse-train correlators are employed to provide the advantages of cross-correlation in improving the reliability of the IFF system. Each of the branches including a pulse-train correlator, threshold device, and binary counter can be assumed to be the same as the system considered in the previous section. With an n-place binary code, there will be 2^n possible different codes, and each of the correlators would be set to a different code. A different criterion would be used for setting the threshold voltages V_T than in the previous analysis; however; the most critical interfering signal for a given channel now is not noise, but the signals intended for correlators set for adjacent numbers. Insofar as the output decision device is concerned, three possibilities are presented. First, at the end of the challenge period (during which m challenges have been received) the counter showing the highest count is selected by a maximum-voltage measuring

circuit to indicate the pulse train having the highest probability of being correct. In the second method, the 2^n counters are successively sampled after each pulse train has been received, and any which have received no pulse during the preceding interval are made inoperative for the remainder of the challenge interval. This is continued until only one channel remains in operation. It can be shown[3] that with high probability this is the channel corresponding to the correct pulse train. In the third scheme, a counter threshold K ($K < m$) is set, and the counter reaching this count first identifies the correct pulse train. Because of its relative mechanical simplicity, the system considered in the following will assume the last-mentioned type of decision circuit.

The main purpose of this section is to describe the method of an analysis currently being made to determine for this system the optimum settings for the voltage threshold V_T and counter threshold K; and, coincidently, the expected (average) probability of error for specified received signal-to-noise ratios will be obtained. Unless otherwise indicated, the same assumptions stated in the previous analysis will be made in the present analysis. Since detection occurs before summation, it will be necessary to use the method of eqs. 11 and 12 to find the probability density of the adding-bus voltage (V_Σ). Assuming for purposes of illustrative example that $n = 4$, the following equation can be written for the probability density of V_Σ, $p_0(V_\Sigma)$, for a correlator receiving a correct pulse train

$$p_0(V_\Sigma) = p(R)*p(R)*p(R)*p(R) = [p(R)*p(R)]*[p(R)*p(R)] \qquad (14)$$

where $p(R)$ is given by eq. 1.

For a correlator receiving a signal differing by one digit from its correct pulse train, it can be easily shown that

$$p_1(V_\Sigma) = p(R)*p(R)*p(R)*p(-R) \qquad (15)$$

Likewise,

$$p_2(V_\Sigma) = p(R)*p(R)*p(-R)*p(-R) \qquad (16)$$

$$p_3(V_\Sigma) = p(R)*p(-R)*p(-R)*p(-R) \qquad (17)$$

$$p_4(V_\Sigma) = p(-R)*p(-R)*p(-R)*p(-R) \;. \qquad (18)$$

Equation (1) can be put into a form more convenient for the present analysis if the variables are normalized by letting

$$v = \frac{R}{\sqrt{\Psi_0}} \qquad \rho = \frac{P}{\sqrt{\Psi_0}} = \text{input signal-to-noise ratio.}$$

Then,
$$p(v) = v\,\varepsilon^{-\frac{v^2+\rho^2}{2}}\, I_0(v\rho) \;. \qquad (19)$$

With the above probability densities defined, the first step in the analysis can now be described. It involves determining for a given ρ, the value of the normalized threshold $V(= V_T/\sqrt{\psi_0})$ which provides at the output of the threshold device a minimum average probability of error P_e as defined by

$$2 P_e = P_M + P_F \tag{20}$$

$$\text{where } P_M = \text{probability of a miss} = 1 - \int_V^\infty p_0(V_\Sigma)dV_\Sigma \tag{21}$$

$$\text{and } P_F = \text{probability of a false alarm}^* = \int_V^\infty p_1(V_\Sigma)dV_\Sigma \; . \tag{22}$$

The analysis described above has been made using graphical techniques to evaluate $p_0(V_\Sigma)$, $p_1(V_\Sigma)$, the integrals of eqs. 21 and 22, and to effect the minimization of P_e. Figure 7 shows the form of the distribution densities $p(R)$, $p(R)*p(R)$, and $p_0(V_\Sigma)$ (all for $\rho = 1$) obtained by this procedure. A plot of $p_1(V_\Sigma)$ is shown in Fig. 8. The curves of Fig. 9 show P_M and P_F vs. V_Σ, and their sum, $2P_e$, gives a minimum at the optimum threshold value of $V = 4.55$. The corresponding values (for $\rho = 1$) of P_M, P_F, and P_e are approximately .18, .14, and .16, respectively.

The above represents the extent to which the analysis being described has been so far carried out. The following outlines the procedure to be used in completing the analysis.

After determination of the optimum voltage threshold, attention can be given to the calculation of the optimum counter threshold, K. This is the setting that maximizes the probability that the counter connected to the channel receiving its correct pulse train reaches the threshold first. Or, in other words, it minimizes the sum of the probabilities of no channel count reaching the threshold at all and of some other channel count reaching it first. The first probability is the probability of a miss, $P_M{}'$, and the second is the probability of a false alarm, $P_F{}'$.

For n = 4, there are four component false-alarm probabilities for incorrect signals that are required in the determination of $P_F{}'$. They are:

P_{F_1}, the false-alarm probability when one digit is wrong

$$P_{F_1} = \int_V^\infty p_1(V_\Sigma)dV_\Sigma \tag{23}$$

(where V is the fixed threshold value)

* In the present analysis, an approximation is being made in that the effect of noise occurring during the spaces within the pulse train is being neglected. It seems reasonable to assume that the false-alarm probability will be controlled by the adjacent-channel V_Σ. In any case, at the expense of considerable complication, this effect of noise can be included as will be discussed later.

P_{F_2}, the false-alarm probability when two digits are wrong

$$P_{F_2} = \int_{V}^{\infty} p_2(V_\Sigma)\,dV_\Sigma \tag{24}$$

where $p_2(V_\Sigma)$ is given by eq. 16

P_{F_3}, the false-alarm probability when three digits are wrong

$$P_{F_3} = \int_{V}^{\infty} p_3(V_\Sigma)\,dV_\Sigma \tag{25}$$

and P_{F_4}, the false-alarm probability when all four digits are wrong

$$P_{F_4} = \int_{V}^{\infty} p_4(V_\Sigma)\,dV_\Sigma. \tag{26}$$

After noting that the probability P_s that the correct correlator produces a count of one at the counter is

$$P_s = \int_{V}^{\infty} p_0(V_\Sigma)\,dV_\Sigma, \tag{27}$$

the probability $\theta(k)$ that the correct counter will reach a count of k first can be written as

$$\theta(k) = \sum_{i=k}^{m} \theta_i(k), \tag{28}$$

where $\theta_i(k)$, the probability that the "correct" counter reaches a count of k first on the i-th trial, is given by

$$\theta_i(k) = [C_{k-1}^{i-1} P_s^k (1 - P_s)^{i-k}]\cdot[\sum_{x=0}^{k-1} C_x^i P_{F_1}^x (1 - P_{F_1})^{i-x}]^4\cdot$$

$$[\sum_{x=0}^{k-1} C_x^i P_{F_2}^x (1 - P_{F_2})^{i-x}]^6\cdot[\sum_{x=0}^{k-1} C_x^i P_{F_3}^x (1 - P_{F_3})^{i-x}]^4\cdot$$

$$[\sum_{x=0}^{k-1} C_x^i P_{F_4}^x (1 - P_{F_4})^{i-x}]. \tag{30}$$

The first factor in eq. 30 gives the probability of the correct counter reaching a count of k on the i-th trial. The product of the last four factors gives the probability that none of the other $2^n - 1$ correlators will reach the count of k on or before the i-th trial. Thus, $\theta_i(k)$ as written gives the probability that the correct counter reaches a count of k first on the i-th trial. By use of eq. 28, we obtain $\theta(k)$, the probability of a "success" in the process of determining which challenge was transmitted.

The probability $\mu(k)$ that none of the counters will reach k can be written as

$$\mu(k) = \left[\sum_{x=0}^{k-1} C_x^m P_s^x (1 - P_s)^{m-x}\right] \cdot \left[\sum_{x=0}^{k-1} C_x^m P_{F_1}^x (1 - P_{F_1})^{m-x}\right]^4 \cdot$$

$$\left[\sum_{x=0}^{k-1} C_x^m P_{F_2}^x (1 - P_{F_2})^{m-x}\right]^6 \cdot \left[\sum_{x=0}^{k-1} C_x^m P_{F_3}^x (1 - P_{F_3})^{m-x}\right]^4 \cdot$$

$$\left[\sum_{x=0}^{k-1} C_x^m P_{F_4}^x (1 - P_{F_4})^{m-x}\right]. \tag{31}$$

Equations (30) and (31) can now be used to write an expression for the false-alarm probability $P_{F'}$. This is

$$P_{F'} = 1 - [\theta(k) + \mu(k)] \quad . \tag{32}$$

The probability $P_{M'}$ that no channel count will reach k is $\mu(k)$ as given by eq. 31.

All of the information required to determine the optimum value of the counter threshold, K, is now available. The problem becomes one of finding the value of k for which the sum of $P_{F'}$ and $P_{M'}$ (as given by eqs. 31 and 32) is a minimum. It is to be noted that the different forms of the functions involved have all been handled before in the numerical analyses described in this and the preceding sections.

The preceding has assumed that there is no noise during the space interval, such as would be true if a synchronous system employing some scheme of gating off the noise during the space interval were used. In the more practical system where this is not true, the computations necessary in the determination of the new threshold count become unwieldy unless the use of automatic computing machines is assumed. The symbolism of formulating the analysis is relatively simple, however, and for completeness an outline of the procedure will be included here.

A new value of threshold voltage must be first calculated to take into account the effect of noise during the space interval. The probability P_N of obtaining a count due to noise is given by

$$P_N = \int_V^\infty p_o{}^{(o)}(V_\Sigma)dV_\Sigma \tag{33}$$

where $p_o{}^{(o)}(V_\Sigma)$ can be obtained by evaluating $p_o(V_\Sigma)$ for $\rho = 0$, or directly from eq. 1. The false-alarm probability now takes the form

$$P_F^! = P_F + P_N \tag{34}$$

where P_F is given by eq. 22 and P_N by eq. 33. The new value of threshold voltage is the value of V which makes the sum of $P_F^!$ and P_M a minimum. (P_M is again the value determined by eq. 21)

The probability P_s given by eq. 27 and the false-alarm probabilities given by eqs. 23-26 will need to be redetermined for the new value V. Letting these new values be $P_s^!$, $P_{F_1}^!$, $P_{F_2}^!$, $P_{F_3}^!$, and $P_{F_4}^!$, the new value of $\theta(k)$ is given by

$$\theta'(k) = \sum_{i=k}^{m} \theta_i'(k) \tag{35}$$

where $\theta_i'(k) = \theta_{i1} + \theta_{i2}$

$$\theta_{i1} = Q_{i0}\, Q_{i1}^4\, Q_{i2}^6\, Q_{i3}^4\, Q_{i4}$$

$$\theta_{i2} = S_{i0}\, S_{i1}^4\, S_{i2}^6\, S_{i3}^4\, S_{i4}$$

in which $Q_{i0} = \sum_{x=0}^{k-1} [C_x^{i-1}\, (P_s^!)^{x+1}(1 - P_s^!)^{i-1-x}\, C_{k-1-x}^{i-1}\, P_N^{k-1-x}\, (1 - P_N)^{i-k+x}]$

and $Q_{in} = \sum_{x=0}^{k-1} [C_x^i(P_{F_n}^!)^x(1 - P_{F_n}^!)^{i-x} \sum_{j=0}^{k-1-x} C_j^{i-1}\, P_N^j\, (1 - P_N)^{i-1-j}]$

$n = 1, 2, 3, 4.$

The new value of $\mu(k)$ is given by $\mu'(k) = R_o\, R_1^4\, R_2^6\, R_3^4\, R_4$ (36)

where $R_o = \sum_{i=0}^{k-1} [C_i^m(P_s^!)^i(1 - P_s)^{m-i} \sum_{j=0}^{k-1-i} C_j^m\, P_N^j\, (1 - P_N)^{m-j}]$

and $$R_n = \sum_{i=0}^{k-1} [C_i^m (P'_{F_n})^i (1 - P'_{F_n})^{m-i} \sum_{j=0}^{k-1-i} C_j^m P_N^j (1 - P_N)^{m-j}]$$

$$n = 1, 2, 3, 4 .$$

The remainder of the procedure for determining K is the same as that used in the previous analysis where the noise was neglected.

Commentary

As pointed out previously, the analyses just described are to be considered to be of an exploratory nature. Their purpose has been to provide experience in the use of statistical tools for quantitatively studying the reliability of relevant transmission systems. In some cases the idealisations have in obvious ways tended toward the impractical, a freedom which was taken in order to make possible the selection of a mathematical model under which analytical solutions would be possible. It is hoped that future work under this item will include the extension of the methods used in these preliminary analyses to cover more practical examples, and also provide information relating to operation at other values of input signal-to-noise ratio. It is hoped also that it will be possible to check the results of at least some of the analyses by experimental tests. Some of these may be performed on the model of the pulse-train correlator. Others of a more basic nature, such as the effect of the use of a non-ideal detector on the distribution assumed at the input to the correlator, could make use of certain apparatus* constructed under Item I for use in studying the waveforms of speech sounds.

The criterion used in setting the counter threshold has been that which minimises the sums of the unweighted probability that noise (or an incorrect signal) will appear as the correct signal and the unweighted probability that the correct signal will be lost (or called noise), this minimization being made for a fixed input signal-to-noise ratio by varying the number of repetitions over which the counter output is integrated. This is essentially the case of the "ideal observer" described by Middleton[4]. Whether or not this is the best criterion has not been studied. It is intended, however, that some of the future work on this approach will be directed toward this end.

Redundancy Coding

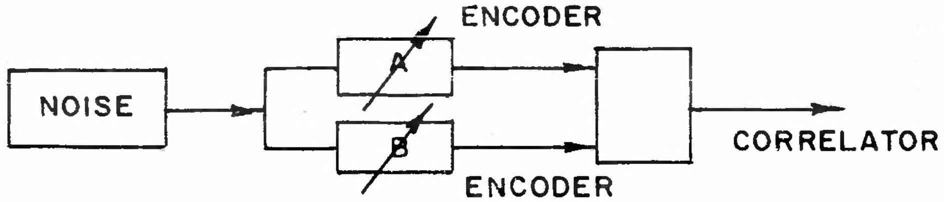
In previous progress reports considerable attention has been given to the use of pulse trains which have additional digits included for the improvement of reliability through redundancy. Studies were made of the number of additional digits theoretically required to match the channel capacity for given assumed noise conditions, and of the reliability which could actually be obtained when the coding period is limited by the length of a challenge or reply. These studies, which assumed a system where a decision is made separately at each pulse position, have been temporarily discontinued in

* See Quarterly Progress Report No. 17 for Item I: Visual Message Presentation of this contract, pp 6 and 7.

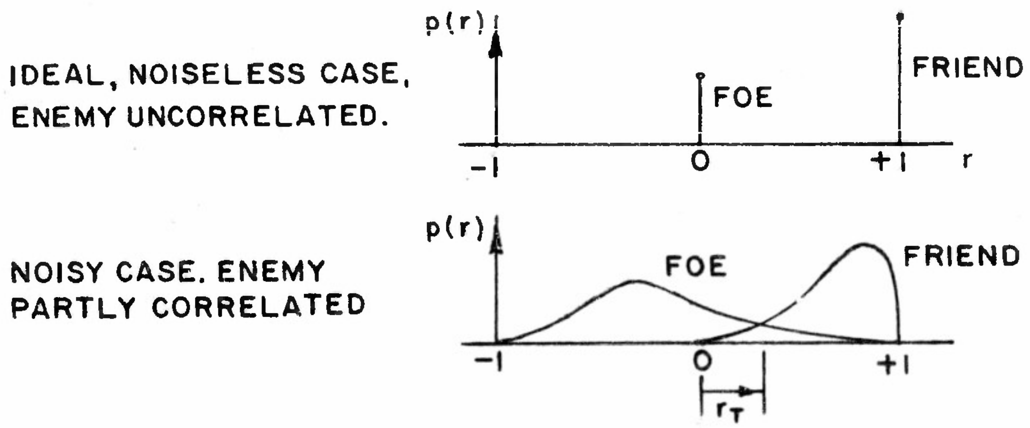
favor of studies of pulse-train correlators as in the preceding section. It should be noted that redundancy in an individual challenge could be used to improve the reliability of the pulse-train correlators at the airplane by increasing (to a number greater than one) the minimum number of digits in which any two challenges may differ, and thereby reducing the worst false-alarm probability. Also the use of either analogue or digital integration of repeated challenges, as proposed in the preceding sections, is redundancy at another level.

Further Conjectures on Using Noise as the Signal

The use of processed Gaussian noise as the challenge and reply signal was introduced in the previous report as a promising means for filling the assigned channel capacity. The basic scheme* considered is that given by the block diagram below, where the path including the A encoder represents the ground-to-air-to-ground link, and the other path a local simulating link at the interrogator-responsor. The two encoders must be identical. While they could be either linear or nonlinear, the present discussion will be limited to the former.



Indication as to whether the interrogated plane is a friend or an enemy is obtained from the correlation coefficient r measured by the correlator. In the ideal noise-less jam-free case, r will have the definite value of + 1 (friend). In the presence of random noise or other interference, r will be more accurately described by a probability density p(r) where the width of the distribution will depend upon the type and intensity of the interference. Likewise, enemy attempts at compromise would result in a second distribution which would be located near r = 0 if the attempts were relatively ineffective. These phenomena can be shown graphically as given below:



* The reader is referred to the previous report for theoretical details of the system and descriptions of encoders and correlator that are being considered.

Consideration of the lower figure shown on the preceding page will reveal that the setting of a reliable threshold, r_T, will be difficult if the distributions are broad. Analogue or binary integration techniques and multiple interrogations can be employed to sharpen the peaks thus causing them to approach more closely the ideal distributions shown in the upper figure. Because of the general unavailability of a suitable continuous storage device, primary attention is being given to the possibility of using binary integration of the type discussed by Harrington[1].

The challenge in thiscase would consist of bursts of encoded* noise, and a decision as to the authenticity of each reply would be made on the basis of whether or not a threshold voltage at the correlater output is exceeded. This decision is stored as a binary number in a counter until some large number m interrogations have been made, whence the storage device is sampled. If the number of positive decisions exceeds a certain number k the reply is judged to be friendly.

Pierce and Hopper[5] have described in a recent paper a novel non-synchronous time-division communication system which incorporated two innovations directly applicable to this scheme as reliability-improving features. Their scheme allows an indefinitely large number of transmitters and receivers to have access to a channel of limited bandwidth. This is accomplished by not employing functions from a truly orthogonal set, but functions from an approximately orthogonal set - such as the noise bursts considered above.

The first feature borrowed from their scheme involves non-uniform spacing of the noise bursts used as the challenges and replies. These spacings would be distributed randomly about some mean value, and the same mean spacing would apply to all subscribers using the same channel. The result to be expected is a decided reduction in harmful interference due to overlapping of replies from several interrogators and planes using the same channel.

The second feature borrowed is the doublet type of signal employed by Pierce and Hopper to identify the called party in their system. In the IFF example, the spacing of the pulses in the doublet would be used to provide an additional code. Thus, in addition to the variable R's, L's, and C's involved in the encoders, the system now allows use of a variable T. All four of these parameters could be changed simultaneously to yield a code giving the possibility of a long "security-time interval".

* The encoding is accomplished by appropriate shaping of the frequency spectrum.

Coding Circuitry

Work under Item III is concentrated on the design, construction, development, and evaluation of a reliable shift register for use in the encoder components of the overall IFF system. The fact that several of these are required, and some are involved in airborne equipment, makes it necessary that weight be reduced to a minimum. Hence, it is desirable to consider the use of transistors instead of vacuum tubes for such devices.

The previously reported design and development of a dynamic storage-cell using either delay-line cable or two monostable transistor circuits have been indefinitely postponed. Emphasis at present is being placed on the evaluation of the reliability of a bistable transistor circuit by means of marginal checking techniques.

UNCLASSIFIED

Bistable Transistor Circuit Research

The first work started under the new problem of Item III, as redefined at the request of AFCRC, was the reliability evaluation of a transistor flip-flop circuit* having two stable, non-saturated states, Marginal-checking techniques[7, 8, 9] as developed at the Digital Computer Laboratory, M.I.T., are considered presently as being the best method to employ for reliability tests.

The method of marginal checking necessitates obtaining considerable amounts of data to be used for the plotting of various types of curves. The shape and area included within these plots, whether closed or unclosed, is an indication of the reliability of the circuit considering the two parameters used as variables. For a symmetrical plot, the coordinates designating the nominal value of the parameters being plotted should fall in the center of the enclosed area for optimum reliability.

Plots will be made using many combinations of the following items as parameters: (1) all of the bias voltages applied to the circuit, (2) all of the components used in the circuit, (3) various types of transistors including different transistors of the same type, (4) input pulse-repetition frequency, and (5) amplitude and width of input pulse. Typical of such plots would be collector resistance vs. collector voltage, and collector voltage vs. base resistance. Considering the same two parameters as variables, other plots can be made as follows: (1) all other parameters at nominal values, (2) one or more of the other parameters offset from this nominal value by a specified percentage, and (3) the other parameters offset from their normal values by amounts considered to create the "worst" possible combination of parameters. It is expected that the accomplishment of the above will provide the necessary information for determining the design center and nominal values of components to be used, as well as an evaluation of reliability of the circuit.

All tests made during this past report period were used to determine the feasibility of obtaining data for use in carrying out the marginal-checking procedure. In no case has any attempt as yet been made to explain

* This circuit [6] was designed by A. W. Carlson of AFCRC.

either the shapes of the plots or the reasons for failure of the circuit. Explanations will be included as more complete and accurate data are taken.

Some of the results of these tests as shown in Figs. 10, 11, 12 and 13 of the Appendix, indicate that data taking for the marginal-checking method of determining reliability should not be difficult. These preliminary tests also afforded an opportunity to develop experimental techniques for obtaining good data. It was found that accurate high-impedance voltmeters (greater than 20,000 ohms per volt and 1 percent accuracy) were necessary to obtain reliable readings. A Wheatstone Bridge was set up for making all resistance measurements.

In the preliminary tests, only two Transistor Products Type 2C transistors were used. These are labelled as numbers 2C-207 and 2C-245 for our own identification system. These two transistors were chosen primarily because they have a cutoff frequency greater than 5 mc, an alpha of greater than 2.5, and a rise time of less than 0.1 μs.

A circuit diagram of the transistor flip-flop used is shown in Fig. 14. All nominal values of components and voltages are shown on the diagram. In all tests performed a pulse repetition rate of 1 mc and a pulse width of 0.1 μs at the base were used.

Figures 10 and 11 show plots of V_{cc} vs. R_b and V_{cc} vs. R_c for a negative pulse of 12.5 volts amplitude and all other parameters at their nominal values. Figure 12 shows the plot of V_{cc} vs. R_b for a negative pulse of 8.5 volts amplitude and R_c = 2.4K, and Fig. 13 shows the plot of V_{cc} vs. R_c for a negative pulse of 8.5 volts amplitude. In all the cases tested to the present, there have been two readings for both the upper and lower failure limits of V_{cc}. That is, for a given R_b (or R_c) one upper failure limit is obtained for V_{cc} by varying V_{cc} from the operative to the non-operative region and another limit by varying V_{cc} from the non-operative to the operative region. A similar condition exists when obtaining the lower failure limit for V_{cc}. In all plots, the limits obtained for V_{cc} were obtained by varying V_{cc} from the non-operative to the operative region. This condition gives the smaller enclosed area of the two, or the maximum area that can be considered to indicate reliable operation.

Transistor Testing

During this report period the transistor-testing program has been continued to provide data for transistor circuitry work done at Northeastern and AFCRC.

A total of 419 Western Electric Type 1698 transistors were tested for AFCRC. Their parameters were in good agreement with average values for this type given in previous reports.* The transistors were tested for the small-signal parameters α, r_{11}, r_{12}, r_{21}, and r_{22}; and α-cutoff. Large-signal testing has been made to determine the rise time and fall time. The measurement of hole storage time has not been made during this report period because of apparent changes produced in the small-signal parameters by this test.

* See Quarterly Progress Reports No. 5 p. 33 and No. 6 p. 28.

To facilitate checking of transistors and to obtain a permanent record of the small-signal parameters, a Dunn Engineering Model 3C Transistor Characteristic Plotter and a DuMont Polaroid Land Camera Type 297 have been ordered. The DuMont camera has been received and the Characteristic Plotter is due in the immediate future.

At the recommendation of AFCRC, equipment is being set up to show plots of α vs. frequency on an oscilloscope screen. A block diagram of the set-up is shown in Fig. 15. It will be possible to use the DuMont Polaroid Land Camera to obtain a picture showing alpha and the frequency response of the transister.

Evaluation of Transistor Products Transtester

During this report period, the reliability of the Transistor Products Transtester was checked by making day-to-day measurements on a group of transistors. The questioning of the trustworthiness of the tester arose from the fact that the values of the small-signal parameters for a transistor tested at Northeastern varied considerably from the small-signal parameter values obtained for the same transistor when measured at AFCRC.

All transistors were tested for frequency cutoff previous to being tested on the Transtester. The transistors were divided into two groups: Group I had frequency cutoffs of less than 3 mc, and Group II had frequency cutoffs greater than 3 mc. All transistors used in this test were checked for the values of the small-signal parameters α, r_{11}, r_{12}, r_{21}, and r_{22} at various collector and emitter biases. The various biases were used to see if reliability was a function of the bias value.

For Group I the calculated alpha $\frac{r_{21}}{r_{22}}$ and measured alpha were found to be within 10 percent of each other. The average values of all the parameters varied only a small percentage from day to day (less than 10 percent). The manufacturer's recommended test points were found to be the optimum bias points for these tests.

For Group II, the measured and calculated values of alpha were within 10 percent of each other. The average values of the tested parameters vary considerably from day to day for some of these transistors. Variations of 10 to 50 percent were common. The parameters of those transistors having the highest values of frequency cutoff exhibited the largest day-to-day percentage variations.

It is probably safe to conclude that all transistors with a frequency cutoff less than 3 mcps will have practically the same measured parameter values from day to day. Slight variation can be attributed to either the physics of the semiconductor or to drift in the calibration of the transtester. No definite conclusions can be drawn to cover the results obtained for transistors in Group II. It was impossible to test some of the transistors in Group II because of their tendency to oscillate while in the tester. Although the tendency to oscillate was found to be a function of the emitter and collector biases, as well as the cutoff frequency, it was not possible to predict the test bias settings at which a particular transistor would oscillate the following day.

e. Apparatus and Equipment

Mock-up System

The test setup which will be used to simulate the air-to-ground link of the IFF system under consideration is shown in Fig. 1. Much of the equipment indicated in the block diagram is available or under construction.

The signal generator and jamming-pulse generator were constructed some time ago and are discussed in earlier reports. The latter produced periodic output pulses and will be replaced by a new model which is under development and will provide randomly-spaced output pulses. Two indentical pulse modulators have been constructed for use as signal-pulse and jamming-pulse modulators. Commercial noise generators are available for use as low-frequency and high-frequency noise sources. A prototype matched filter for i-f pulses has been constructed and will undergo testing and modification in the near future. The pulse-train correlator has been completed and is undergoing trouble-shooting at the present time. A modulator for use with the low-frequency noise source is in the planning stage.

Random-Pulse Generator. A pulse generator is under development which is to produce randomly-spaced constant-amplitude pulses to simulate this type of jamming. The generator will employ a noise source whose output will be filtered, clipped, and differentiated. The resulting randomly-spaced spikes will be used to trigger a blocking oscillator or similar one-shot device.

A new pulse modulator was built during this report period. The pulse modulator described in the previous report had some carrier feed-through that prevented 100-percent modulation. This feed-through seemed inherent to the particular design, hence a different approach was tried.

The new modulator (see Fig. 16) consists of a phase-inverter, a ringing circuit, and a driver tube. The high-Q tank circuit is normally loaded down due to tube V_2 conducting heavily. A negative pulse from the phase inverter cuts off V_2 and causes the high-Q tank circuit to ring. The driver tube V_3 is a cathode follower with a low-Q tank circuit for its cathode impedance. Over a limited frequency range this type of driver circuit can tolerate a moderate amount of capacitative loading since the shunting capacity can be made a part of the low-Q tank circuit. The output waveform was observed by going directly to the plates of a Tektronix Type 514D oscilloscope. For a video pulse input having a strength of 20 volts and a rise time of .01 μs, the r-f pulse output is greater than 10 volts peak-to-peak with an envelope rise time that is less than 0.1 μs. Two of these modulators have been built, one to be used as the pulse-train modulator, the other to be used as the jamming-pulse modulator in the proposed mock-up system.

Filtering. A prototype matched filter for i-f pulses has been constructed in accordance with the theory developed in the previous progress report. The filter, Fig. 17, consists of a delay-line driver and attenuation compensator, V_1 and V_2; a high-Q tank circuit, V_3; and amplifier, V_4. The operation of the various stages can best be described in terms of their impulse responses.

A unit impulse appearing at the input is applied to an open-circuited delay line via the low-impedance driver, V_1. The delay line consists of a length of RG62/U cable which produces a round-trip delay of 0.6 μs. The incident and reflected impulses are applied to the grid of V_3. Due to the attenuation of the delay line, the incident impulse is the larger and consequently the phase inverter, V_2, and its associated adding circuit are used to reduce the incident impulse to the same amplitude as the reflected impulse. Thus two equal impulses, separated by 0.6 μs, are applied to V_3. The first impulse shocks the high-Q tank circuit into oscillation. If the natural frequency of the tank circuit is properly chosen, the second impulse will reduce the amplitude of the oscillation to zero. The final stage, V_4, serves as a broad-band amplifier (the inductance in the plate circuit is resonated against the stray capacity of the output circuit).

At present, the filter works qualitatively but not quantitatively. Further work awaits the construction of a high-impedance, low-capacity probe. At present there appears to be some phase shift in the phase inverter, V_2. Refinement of the weighting networks employed in the adding circuit is necessary. Also the Q of the tank circuit, V_3, must be increased.

Pulse-Train Correlator. Two major modifications were incorporated in the correlator in this report period. It was observed that appreciable amounts of signal were feeding from the maximum and minimum busses into the adding-bus via the diodes and 10-K isolating resistors at those switch terminals which were not at the time connected to the cathode followers and which, therefore, were at a high impedance to ground. To remove this effect it was necessary to replace the two-gang switches by four-gang switches, thus achieving the necessary isolation at the "open" switch terminals.

The other change consisted in replacing the "A" and "B" direct-coupled amplifiers by cathode followers, which are coupled to the adding-bus by resistors so chosen as to give the proper proportions of "A", "B", and addition voltages. This modification necessarily lowered the signal level in the adding-bus, wherefore a single two-stage d-c amplifier was provided between it and the threshold diode. For greater stability this amplifier was designed with balanced gain-stages, which are followed by a single-ended cathode follower output.

The complete, modified circuit of the correlator is shown in Figs. 18 and 19.

It recently has become apparent that the pulses, in passing down the delay-line, are changed from a rectangular to a triangular shape, and that it is this change of pulse-shape that stands in the way of proper addition and cancellation in the adding-bus. For the near future, therefore, a program of pulse-shape matching is anticipated. It is hoped that this can be accomplished to a sufficient extent by the introduction of single-section, low-pass R-C filters in the grid circuits of the phase-inverter stages.

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Coding Circuitry

A transistorized flip-flop circuit with two stable, non-saturated states has been constructed and used for all tests performed under Item III. A schematic diagram of the circuit is shown in Fig. 14 of the Appendix.

A battery power pack was built to facilitate taking marginal-checking data. The pack supplies voltages from -67.5 volts to + 67.5 volts in 1.5 volt steps. A 100-ohm potentiometer is used as a divider between the 1.5 volt steps to get exact voltage measurements.

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* * *

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g. Conclusions and Recommendations

As a result of the work of this report period it is concluded that:

1. The signal-pulse and jamming-pulse modulators are satisfactory for use in the mock-up system.

2. The matched filter for i-f pulses shows promise of success since all component circuits operate qualitatively.

3. The pulse-train correlator shows promise of success, in that all component circuits operate satisfactorily, and some results of overall performance have been obtained.

4. The multiple-challenge system described herein can be expected to possess good system reliability despite random or planned interference.

5. The quantitative analyses of the performance of the pulse-train correlation systems as begun herein provides useful background information for future more-sophisticated treatments of the general problems involved in the specifications and adjustments of such systems.

6. The inclusion of binary integration, random spacing of the noise bursts, and the concept of the doublet type of digit symbol, in the consideration of an IFF system using noise as the signal should result in increased reliability for that type of system.

7. The marginal-checking method for the evaluation of the reliability of transistor circuits can be used successfully.

8. The Transistor Products Transtester operates satisfactorily for all transistors having a frequency cutoff less than 3 mc.

9. The alpha vs. frequency plotter facilitates the measurement of frequency cutoff for transistors. It is recommended that work be continued to improve and extend the overall frequency response of the system.

h. Future Work

In view of the work of this and previous report periods, and the above conclusions and recommendations, it is intended that future work include:

1. The construction and testing of the units of the mock-up system not as yet worked on, and the eventual assembly and use of the entire system.

2. The construction of a noise modulator for use with the mock-up system to simulate noise jamming.

3. Completion of the development and construction of the random-pulse generator.

4. The modification of the matched filter so that more accurate performance may be obtained.

5. The remodeling of the pulse-train correlator into its final form, and the testing of the unit. This will include determining its response to any or all of the following inputs:

- (i) The "correct" signal,
- (ii) Any "incorrect" signal (i.e. pulse jam),
- (iii) Noise jam.

6. An elaboration and more detailed analysis of the Multiple-challenge system, special attention being devoted to (1) the effect of random noise, and (2) the problem of combining several four- to six-place correlators so as to be able to handle long challenges without using impractically large and complex equipment.

7. The continuation of the quantitative analyses of the performance of pulse-train correlation systems to cover schemes of greater practicality. This would result in setting specifications covering the design and adjustment of optimum forms of such systems. New procedures to be studied would include the use of the betting-curve type of analysis in determining criteria for the setting of thresholds.

8. Continued study of the use of noise as the challenge and reply signals in an IFF system along the lines indicated in this and the previous report.

9. The continuation of the study of marginal-checking procedures as applied to the evaluation of reliability of transistor circuits.

10. The continuation of the transistor-testing program in its present form to provide data for use in the design and evaluation of transistor circuits.

APPENDIX

a. Curves and Drawings

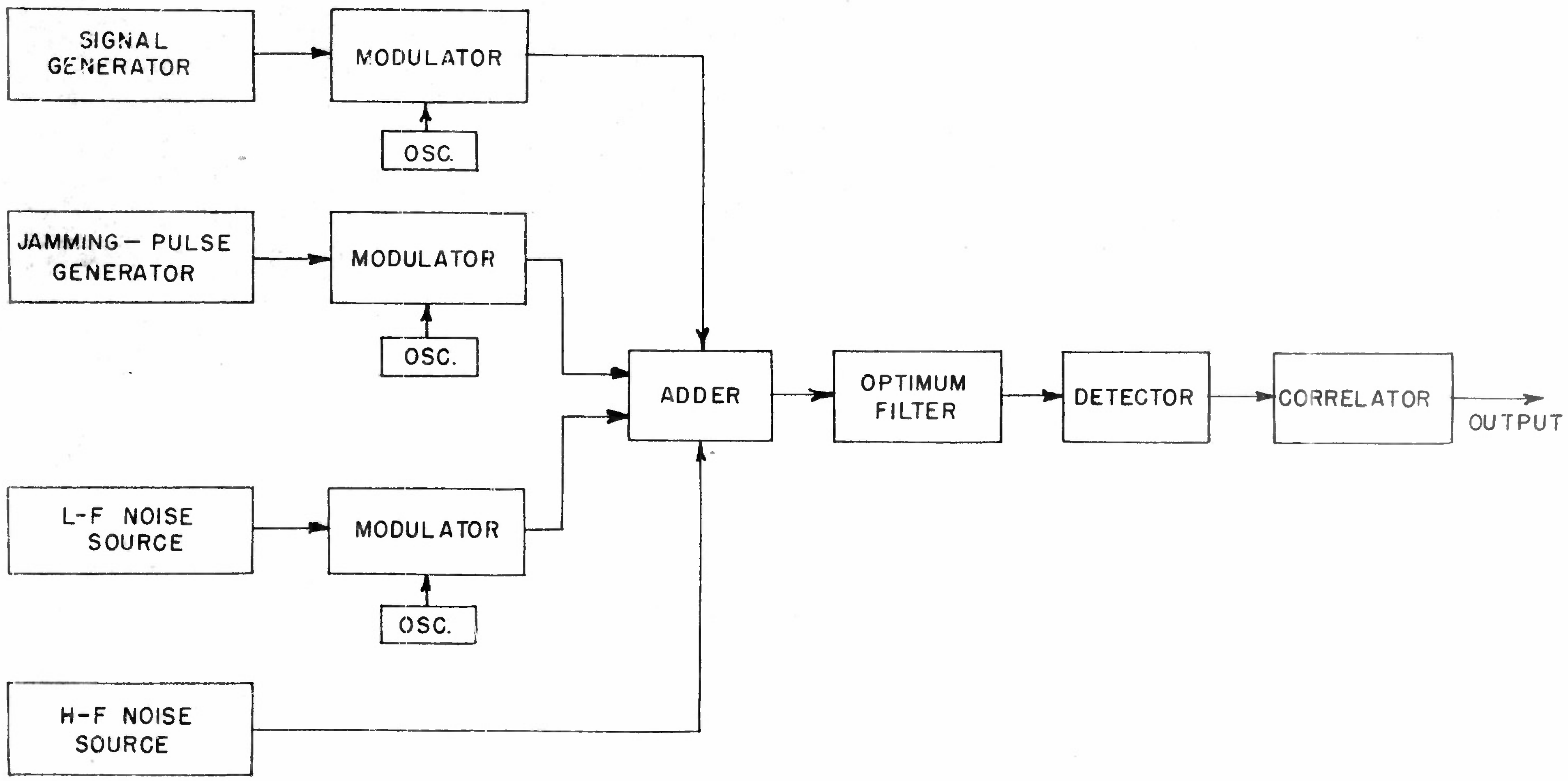


FIG. I. BLOCK DIAGRAM OF PROPOSED TEST SET-UP.

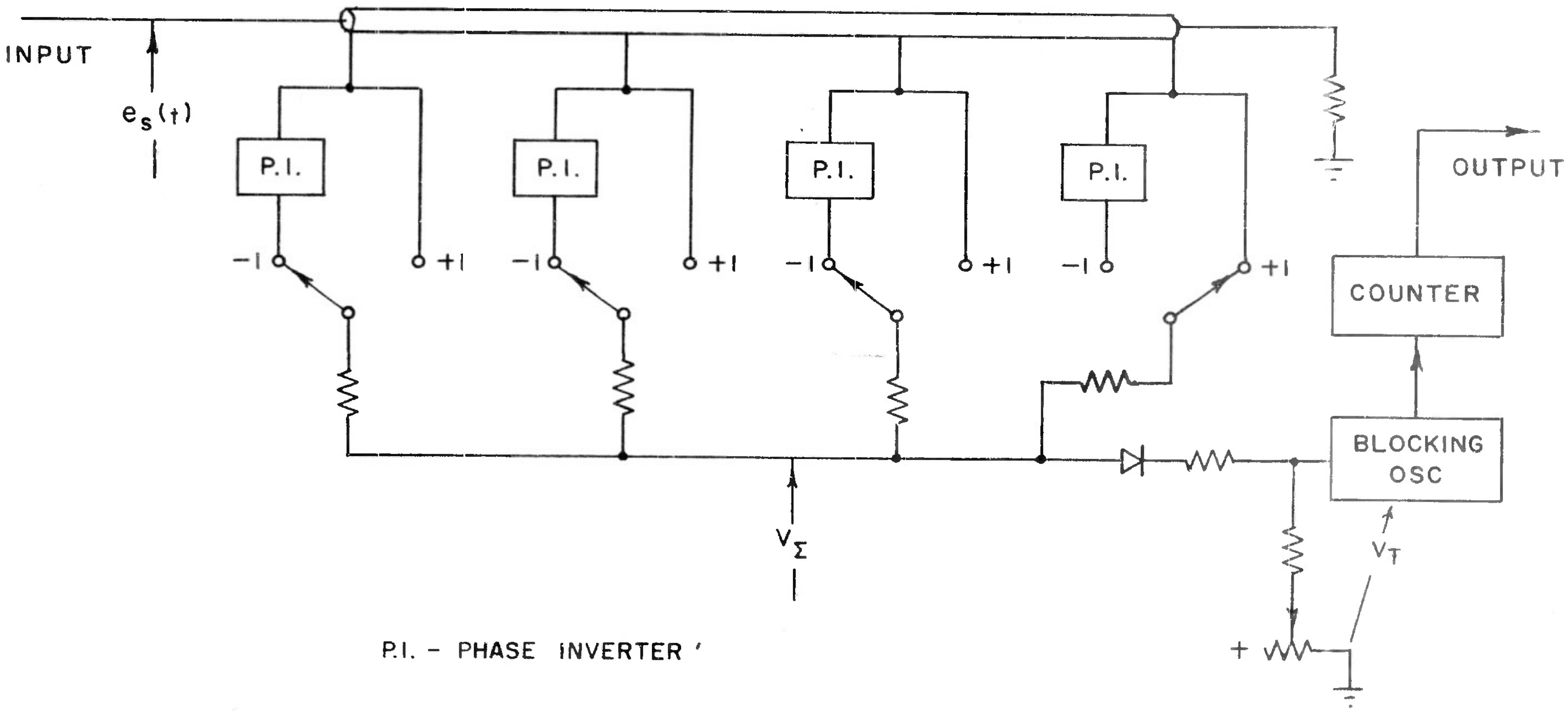


FIG. 2. BLOCK DIAGRAM SHOWING SCHEME ASSUMED IN MAKING THE ANALYSIS OF THE PERFORMANCE OF THE PULSE-TRAIN CORRELATOR.

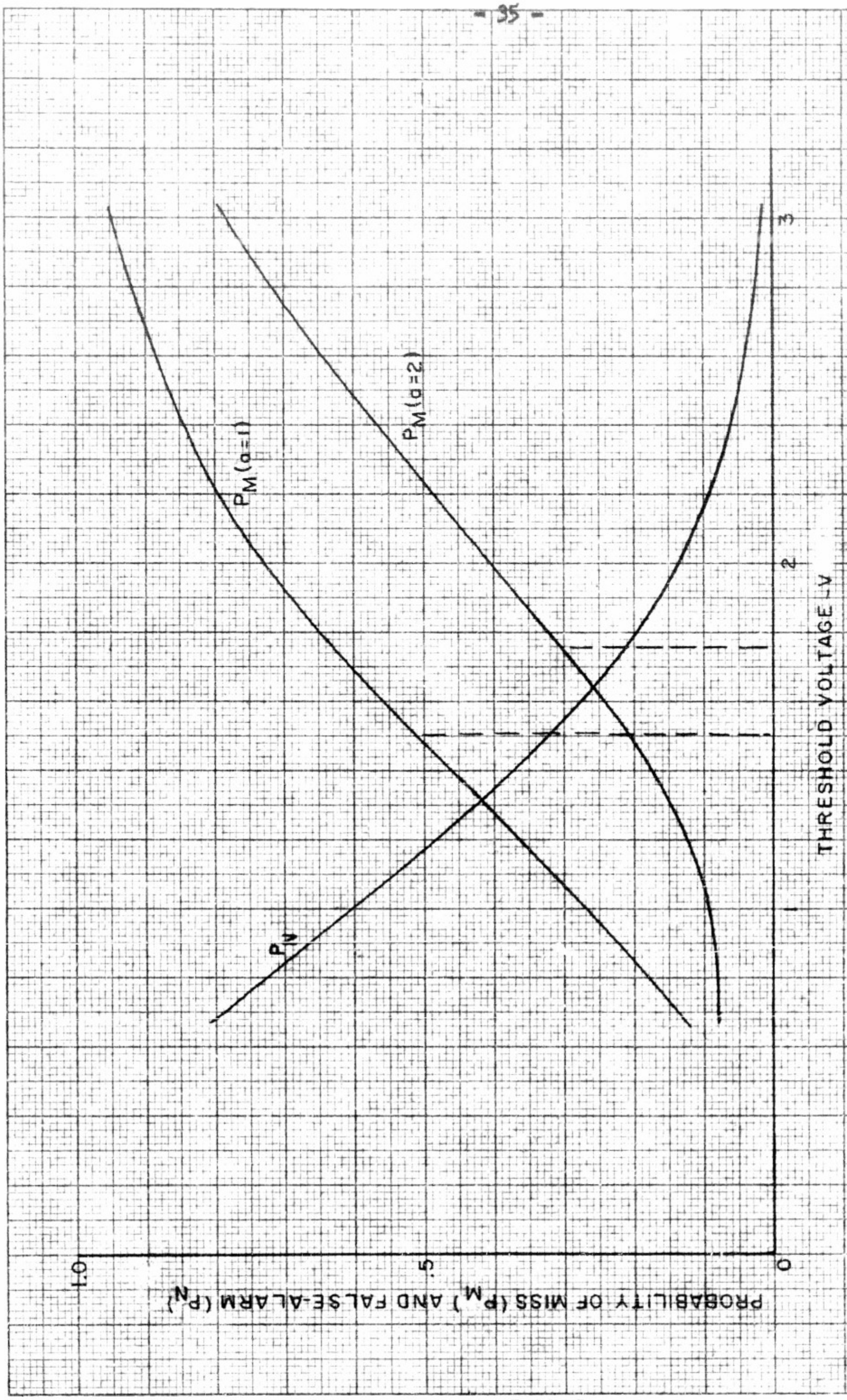


FIG. 3. PROBABILITIES OF MISSES AND FALSE-ALARMS vs. THRESHOLD VOLTAGE.

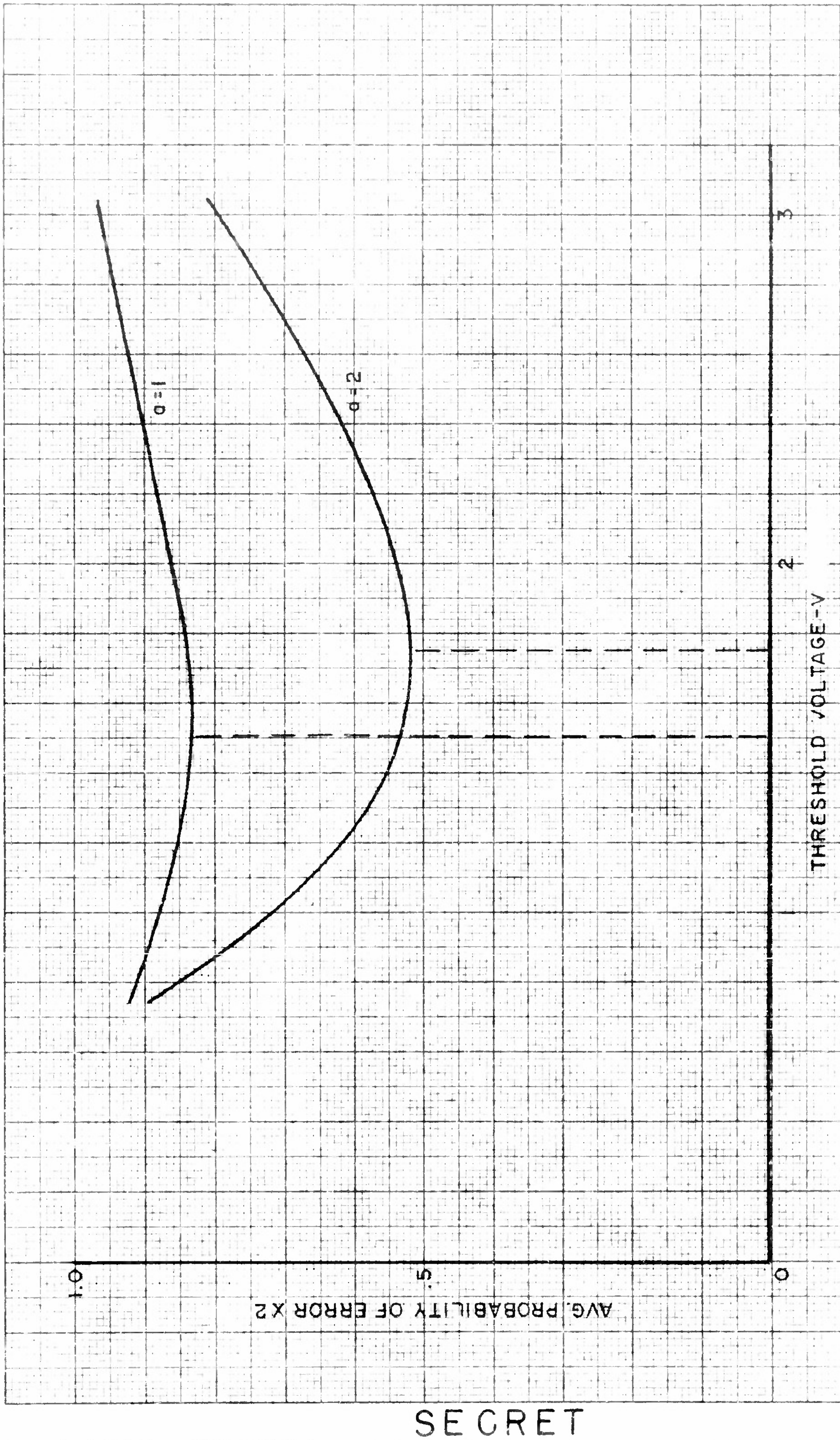
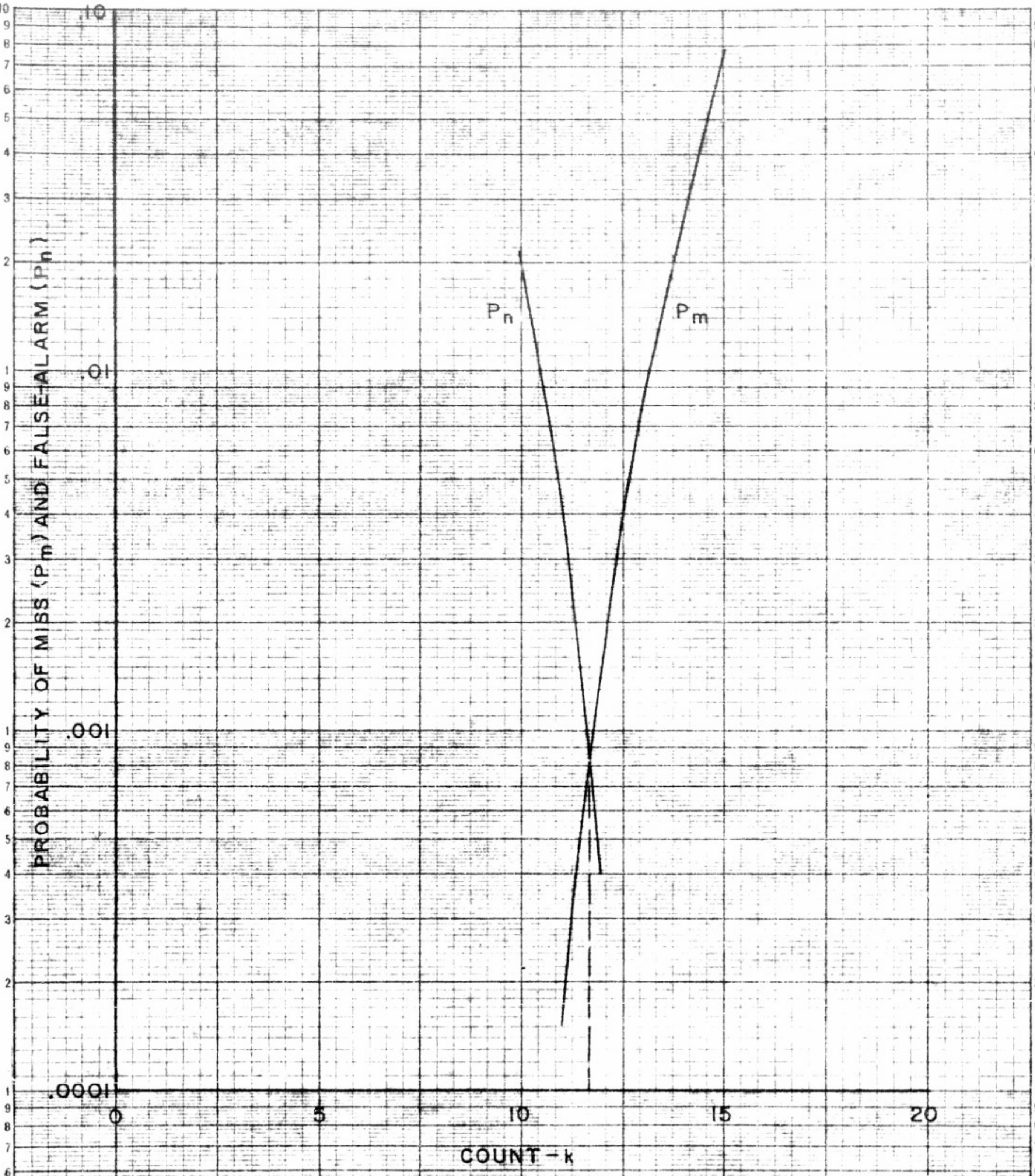
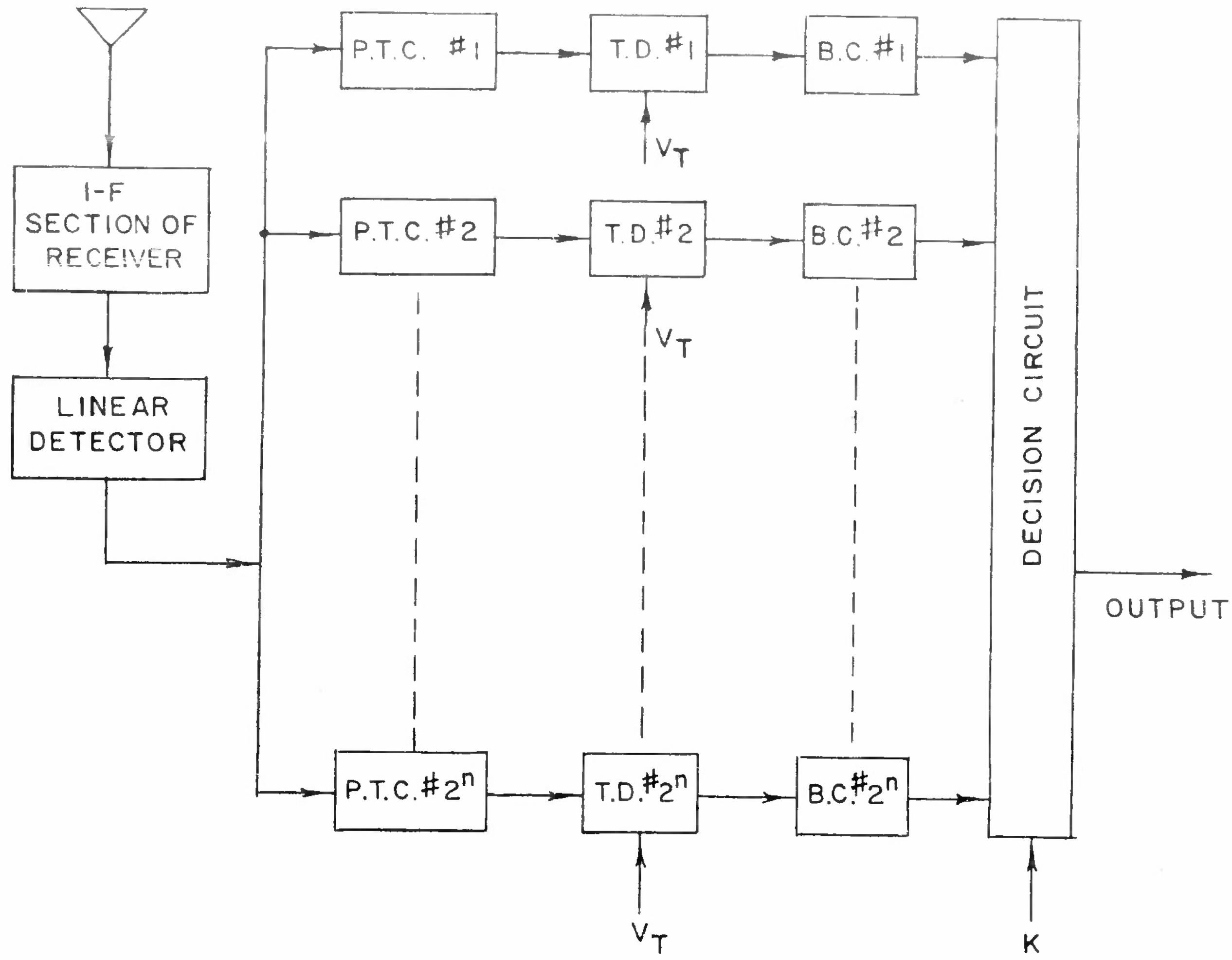


FIG. 4. PROBABILITY OF ERROR vs. THRESHOLD VOLTAGE FOR PULSE-TRAIN CORRELATOR.



($a = 2$, V = OPTIMUM VALUE, $m = 25$)

FIG. 5. PROBABILITIES OF MISSES AND FALSE-ALARMS vs. COUNT.



LEGEND

P.T.C. PULSE-TRAIN CORRELATOR

T.D. THRESHOLD DEVICE

B.C. BINARY COUNTER

FIG. 6. AIRPLANE END OF THE GROUND-TO-AIR LINK ASSUMED FOR ANALYSIS.

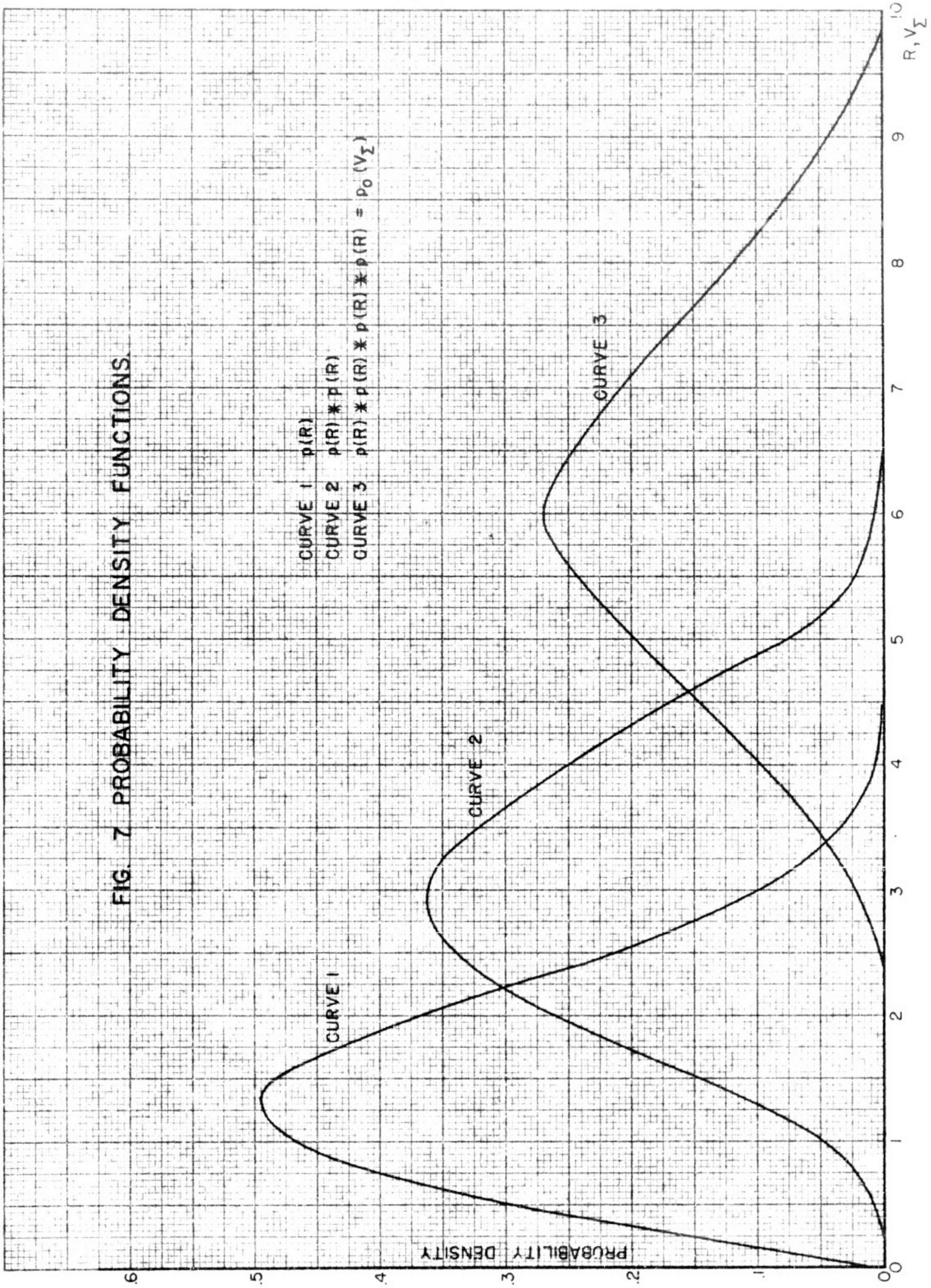


FIG. 7 PROBABILITY DENSITY FUNCTIONS

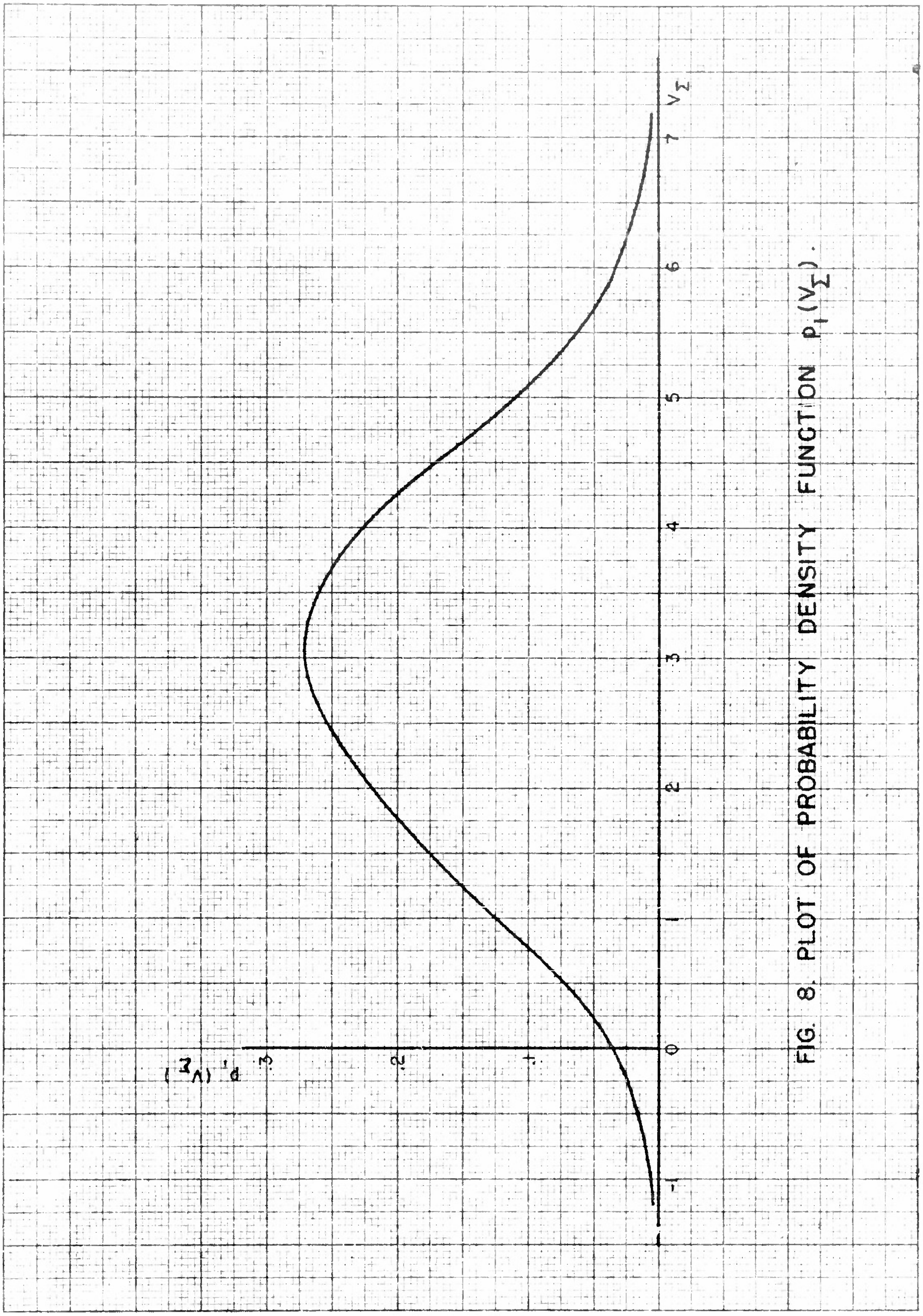


FIG. 8. PLOT OF PROBABILITY DENSITY FUNCTION $p_1(V_\Sigma)$.

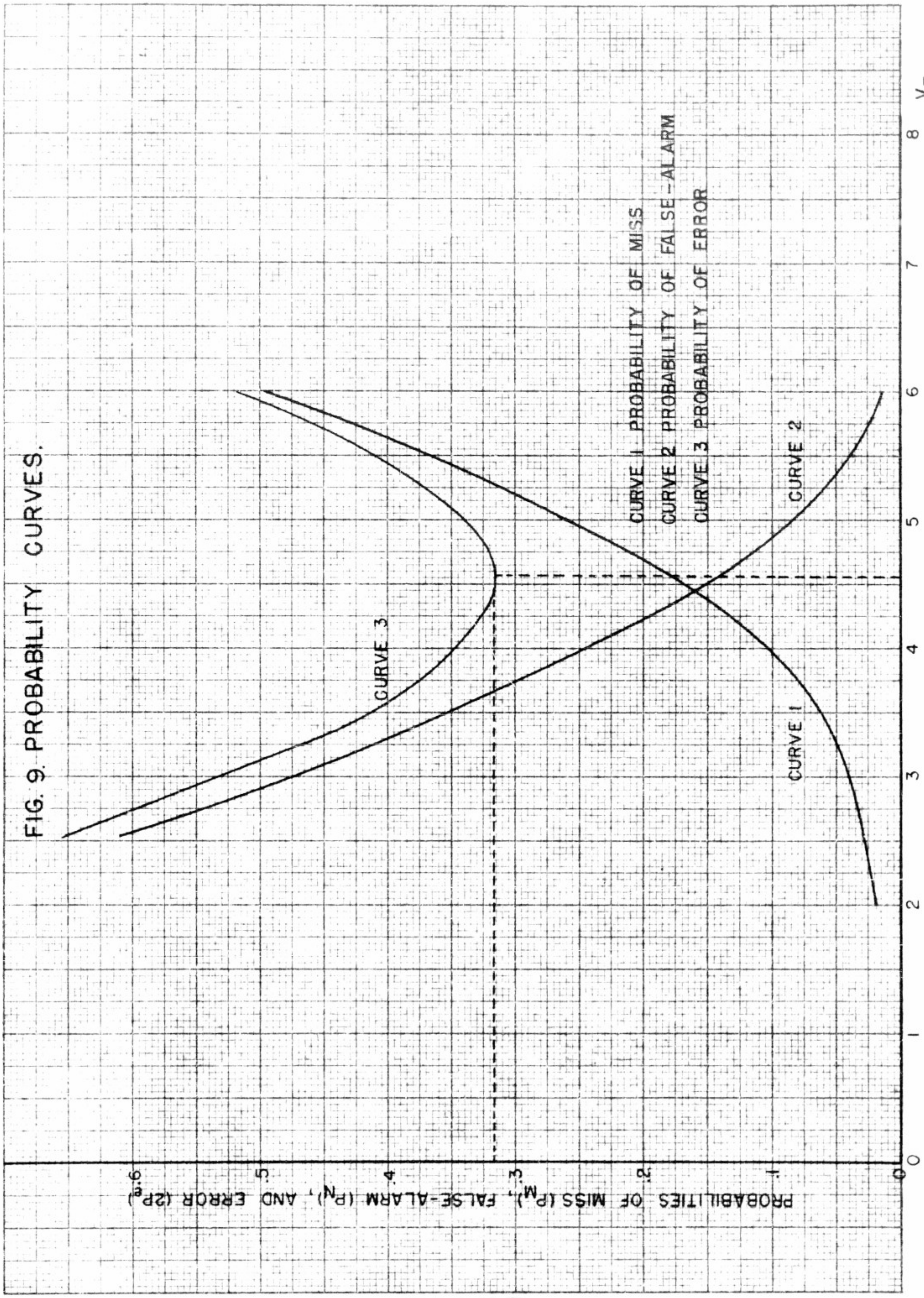


FIG. 9. PROBABILITY CURVES.

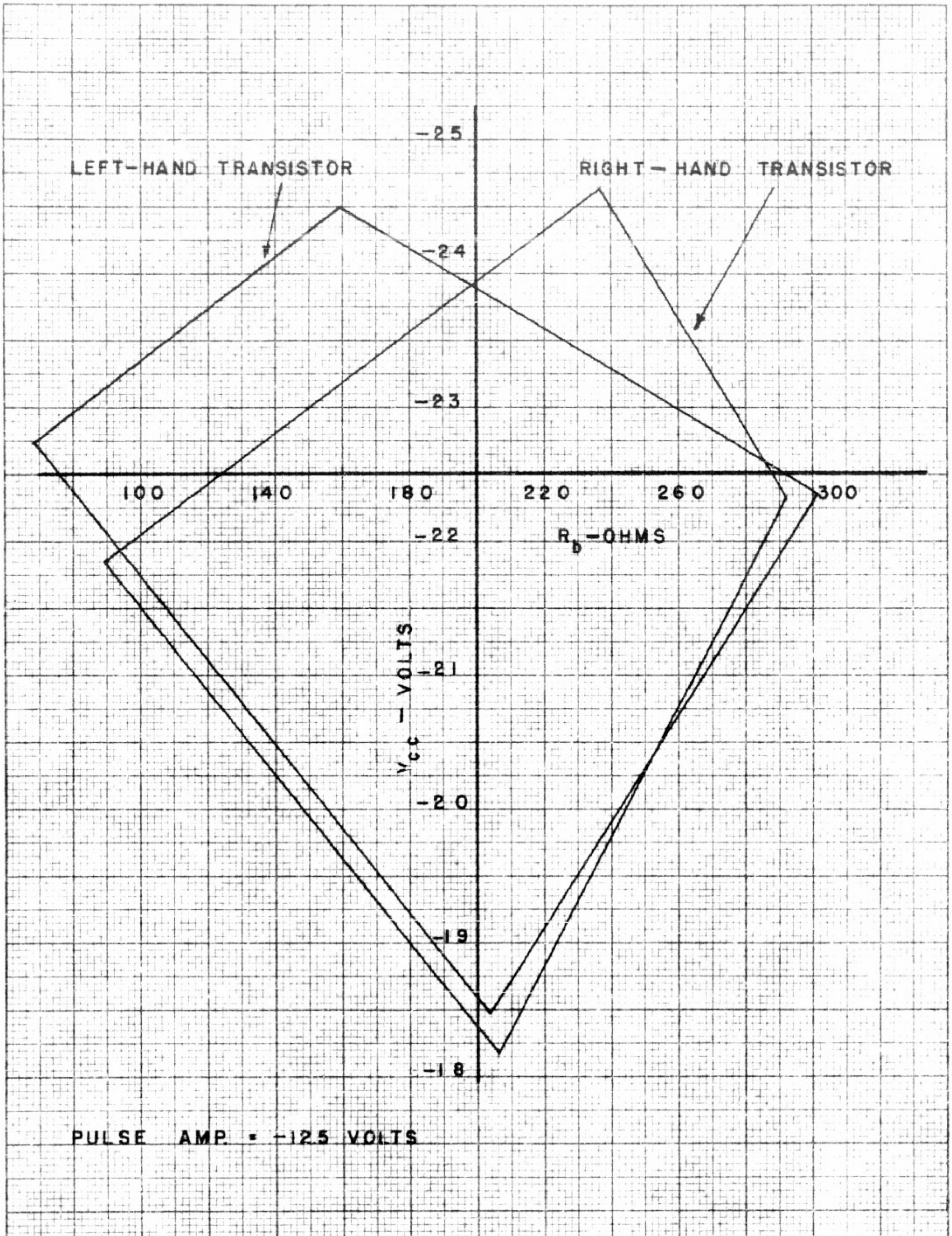


FIG. 10. MARGINAL CHECKING PLOT OF V_{cc} vs. R_b.

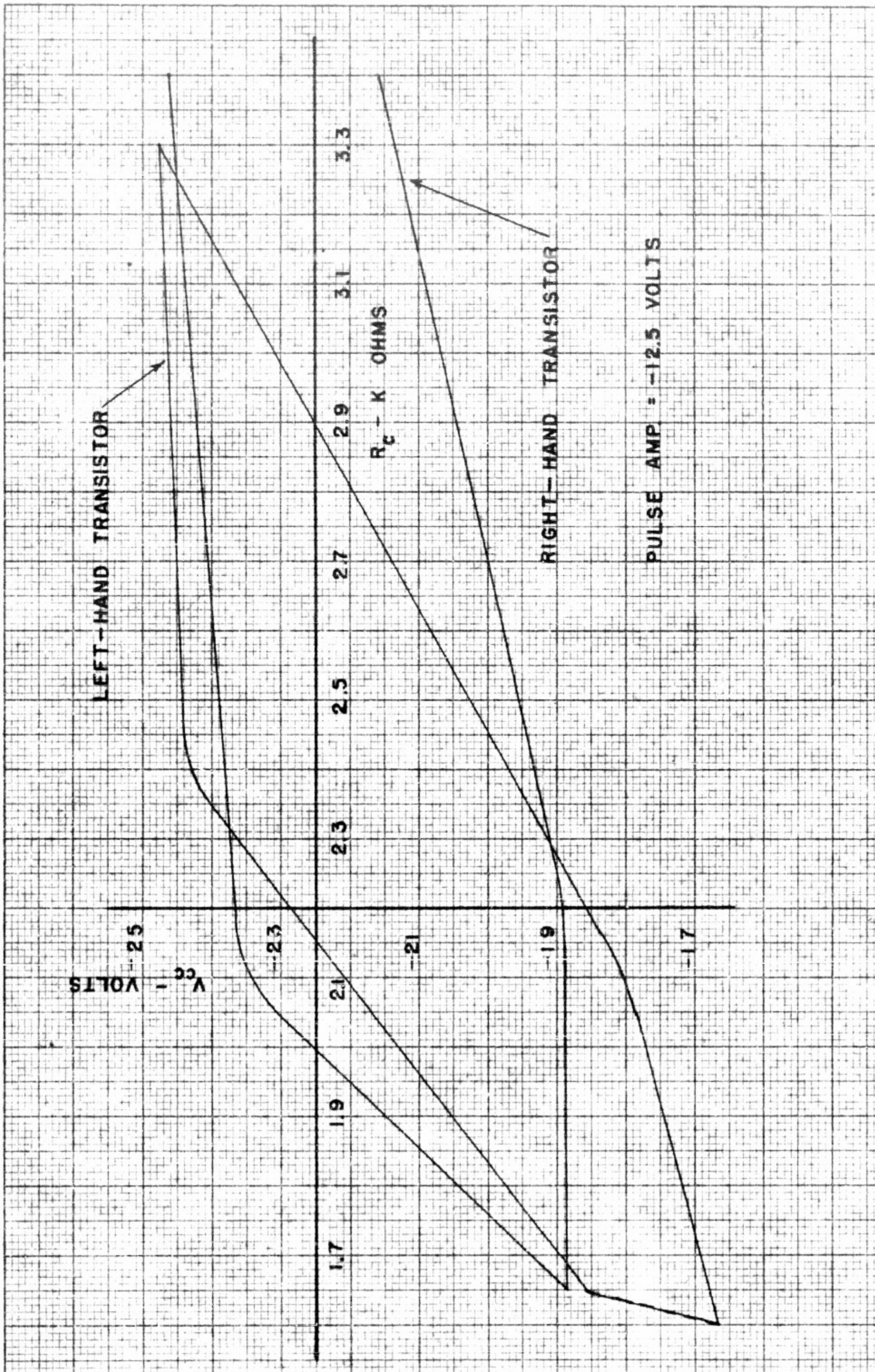
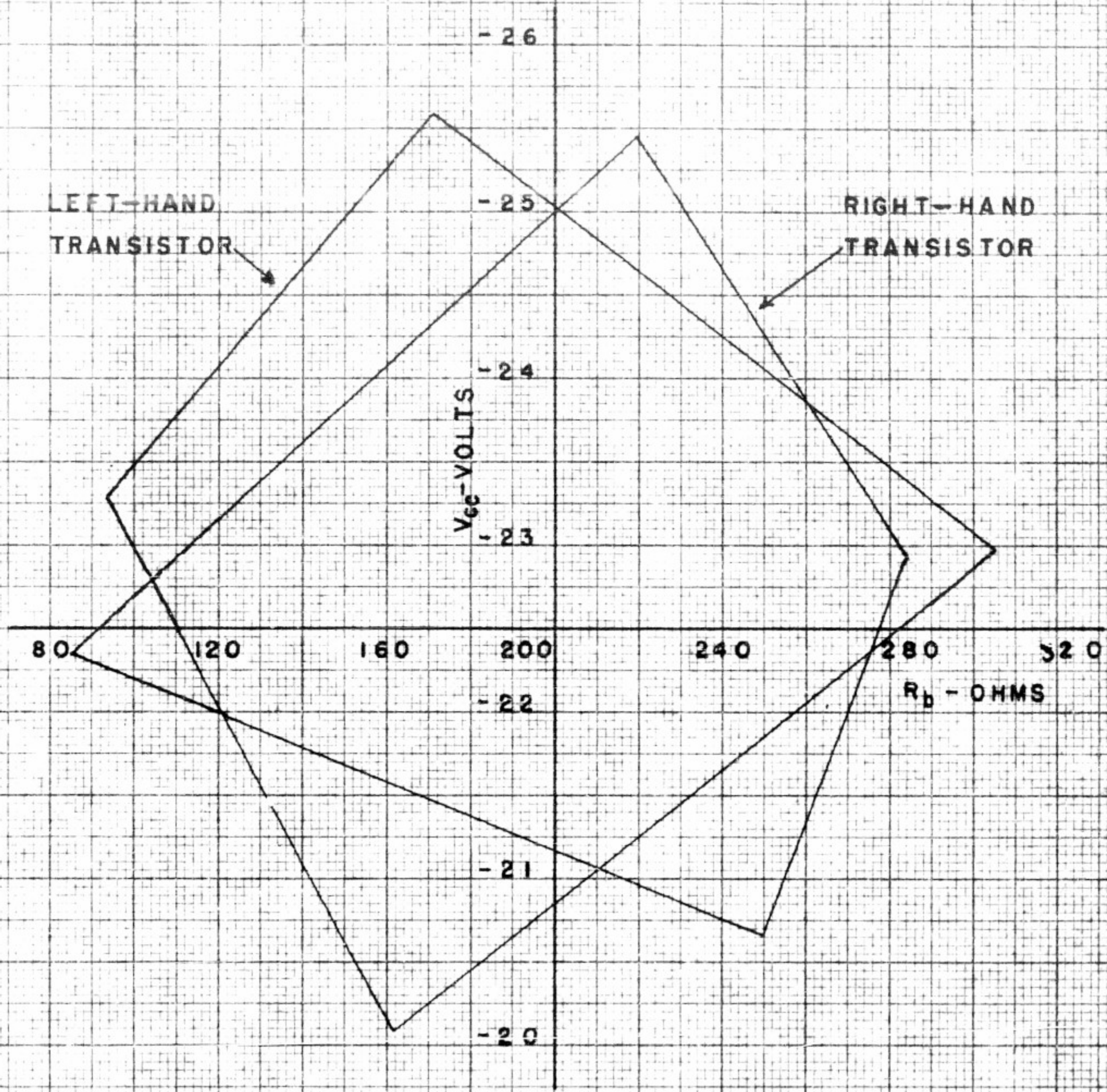


FIG. 11. MARGINAL CHECKING PLOT OF V_{cc} VS R_c.



R_c = 2.4 K OHMS

PULSE AMP. = -8.5 VOLTS

FIG. 12. MARGINAL CHECKING PLOT OF V_{cc} vs. R_b.

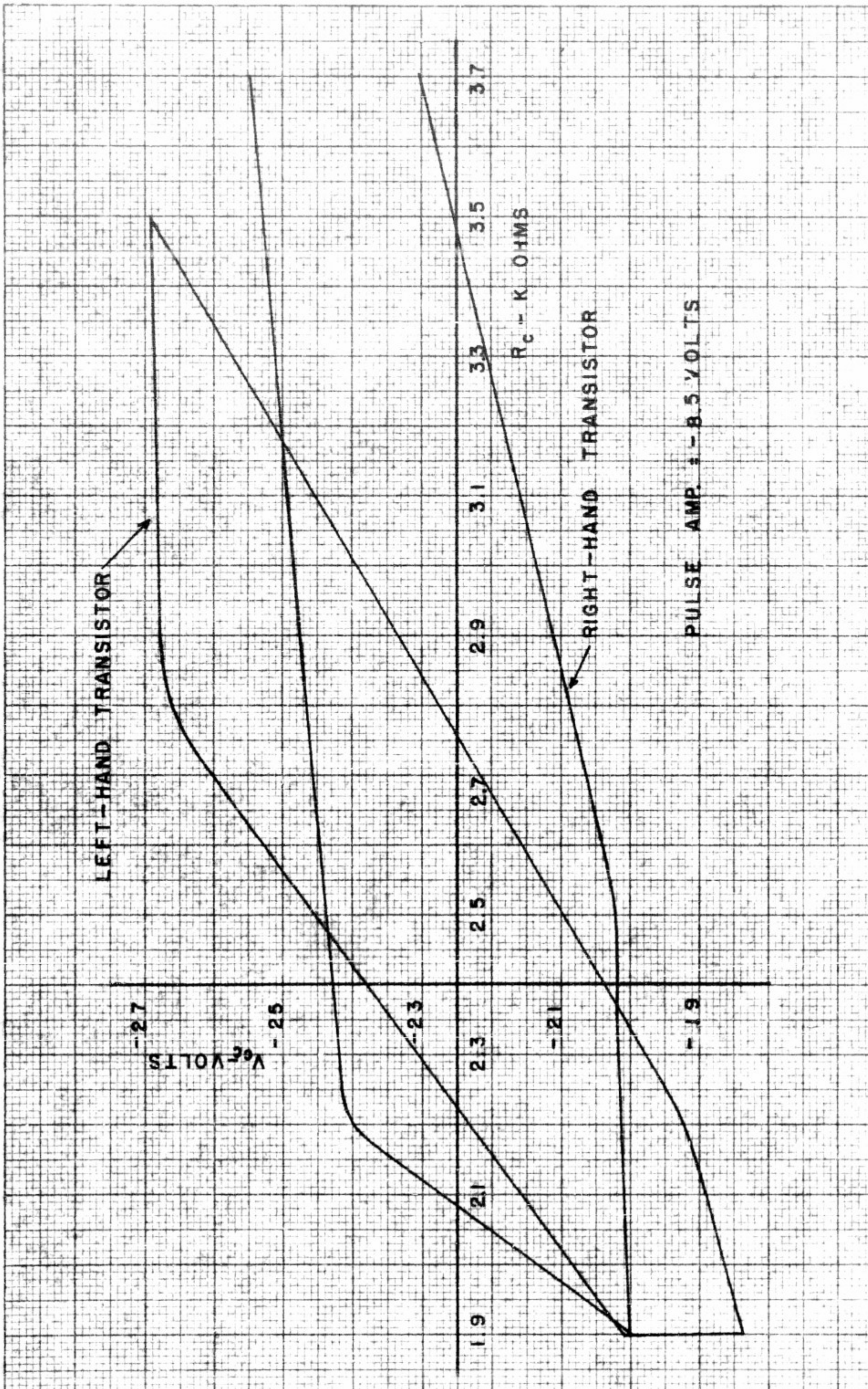


FIG. 13. MARGINAL CHECKING PLOT OF V_{cc} VS. R_c

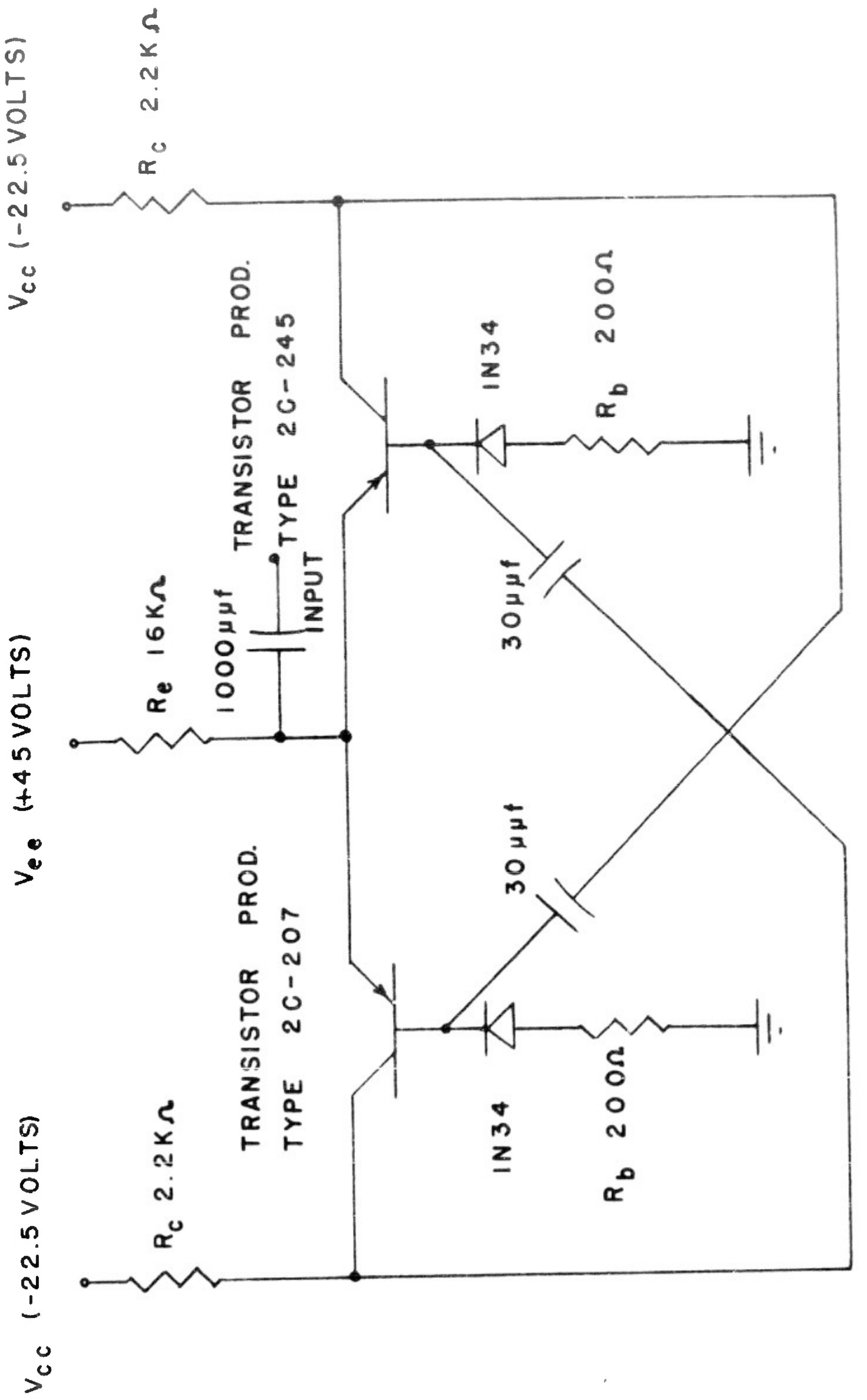


FIG. 14. BISTABLE NON-SATURATING TRANSISTOR CIRCUIT.

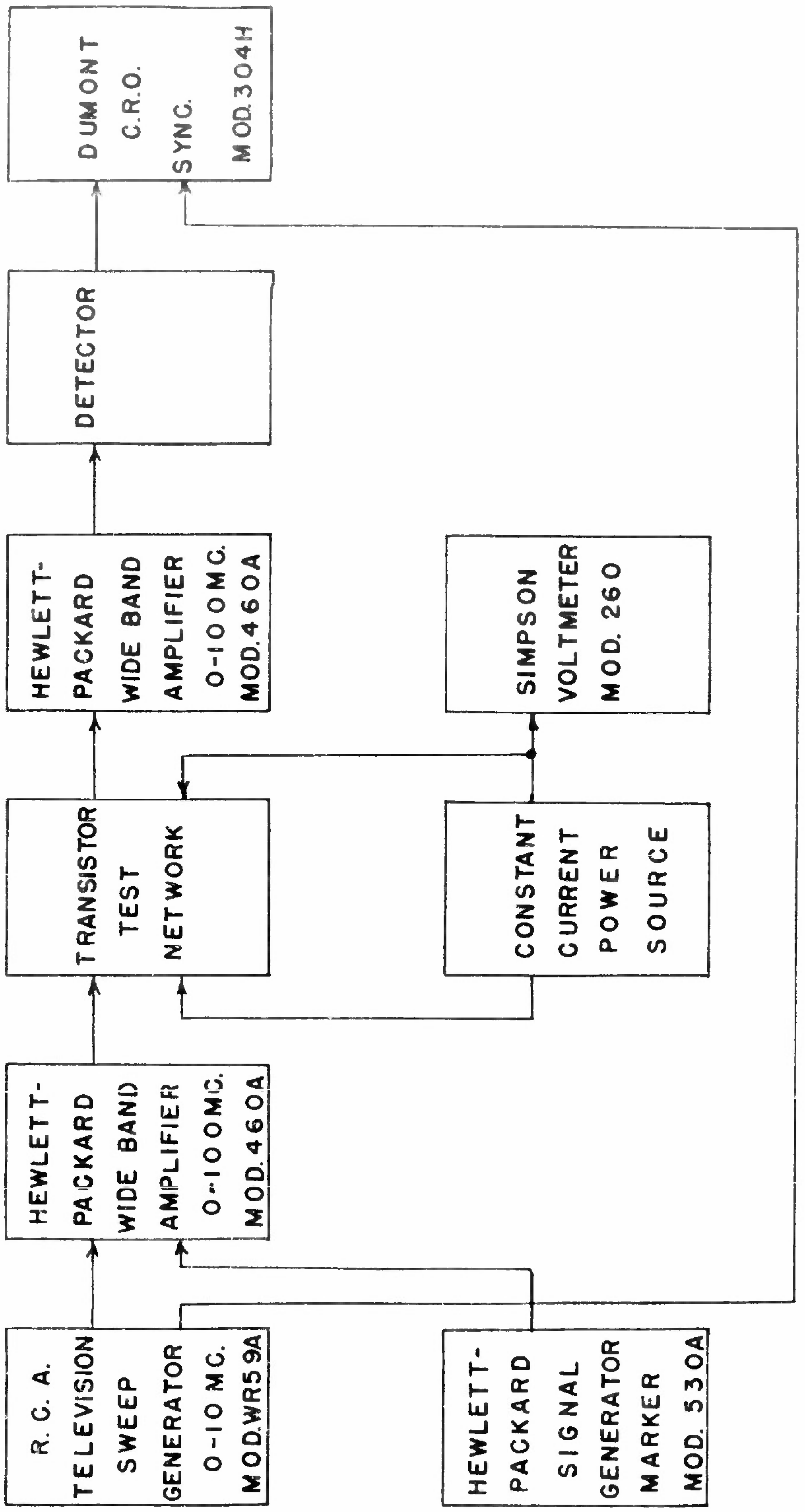


FIG.15. BLOCK DIAGRAM OF TRANSISTOR ALPHA FREQUENCY CUT-OFF PLOTTER.

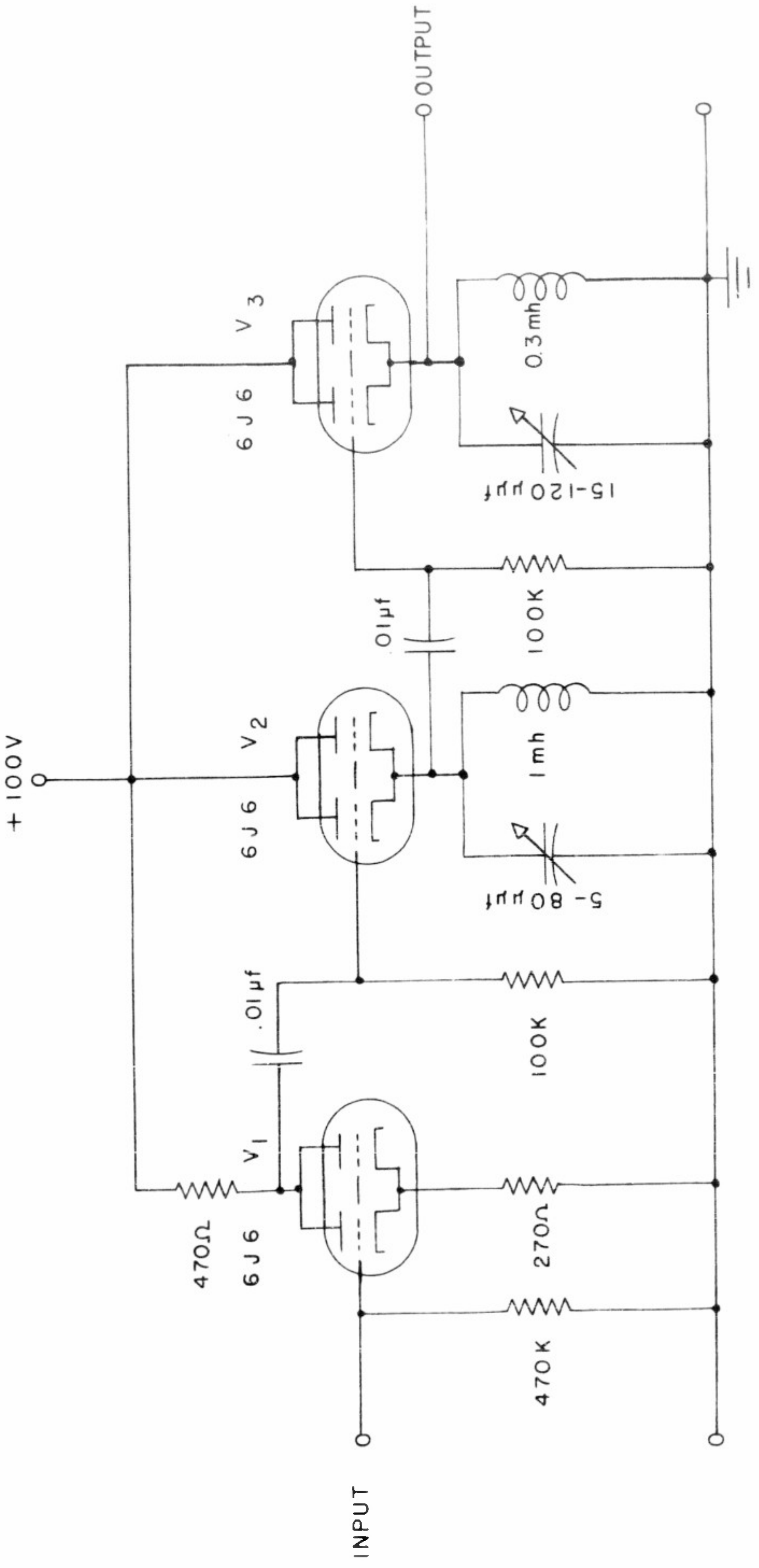
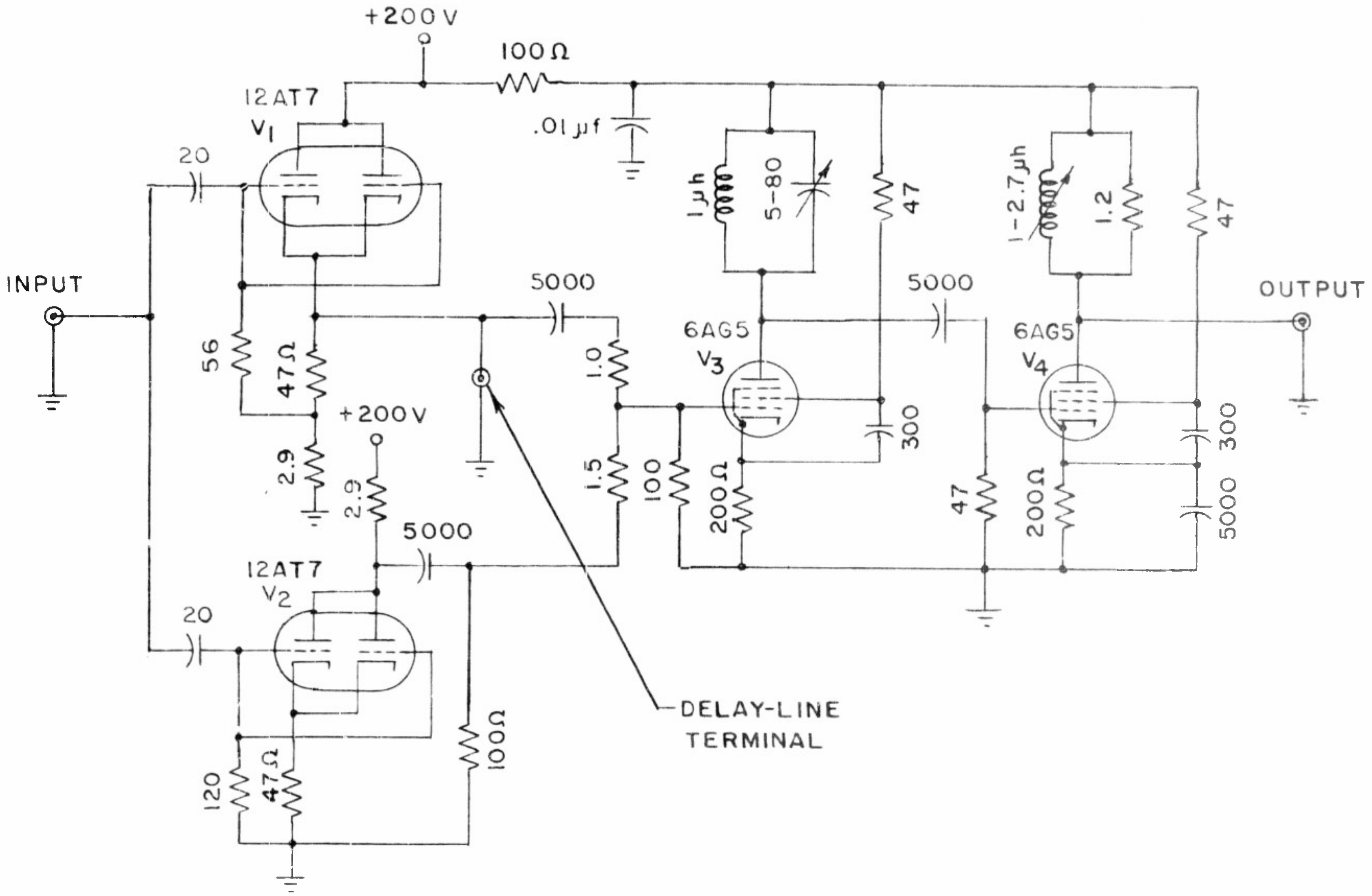
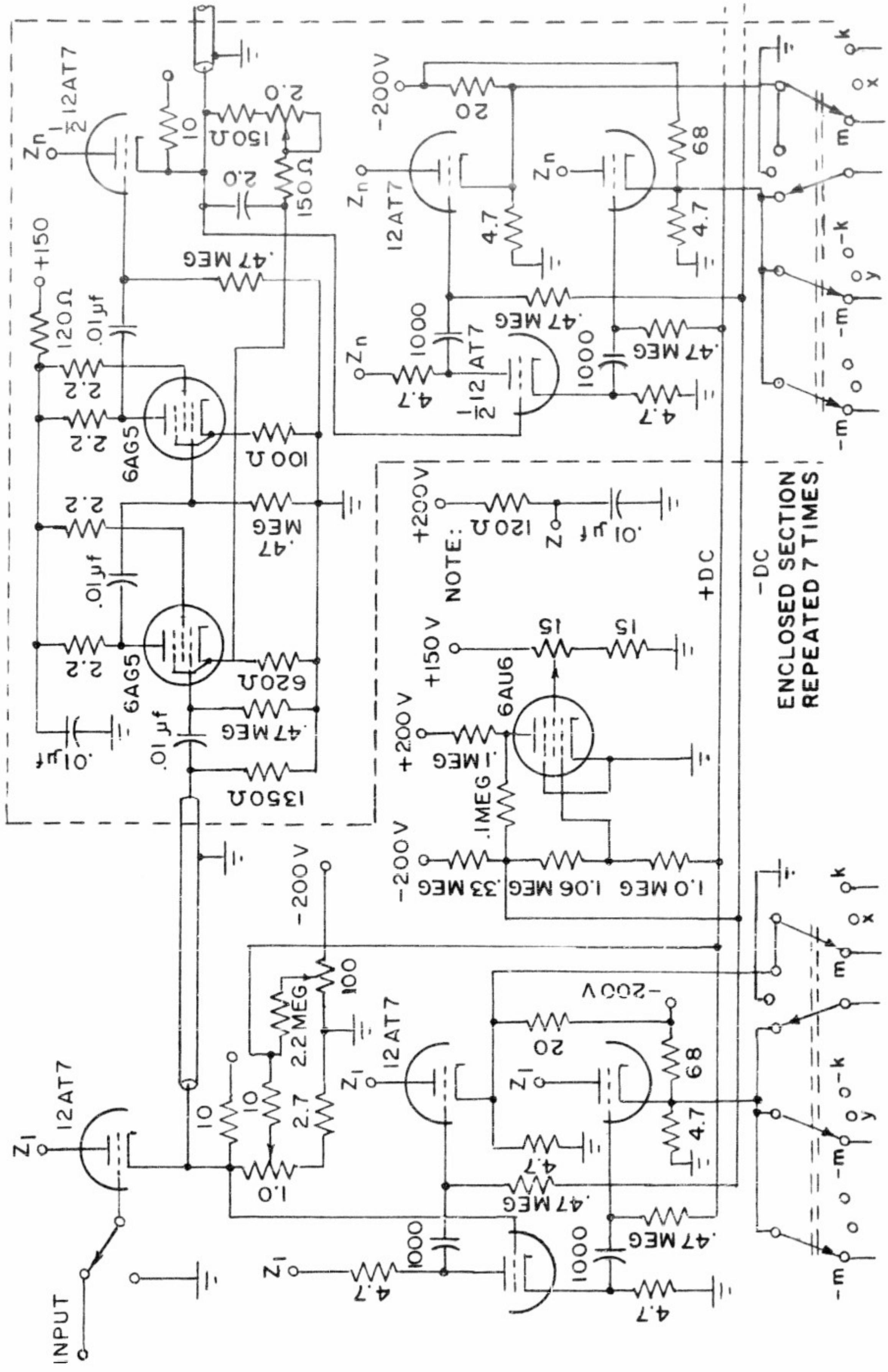


FIG. 16. PULSE MODULATOR.



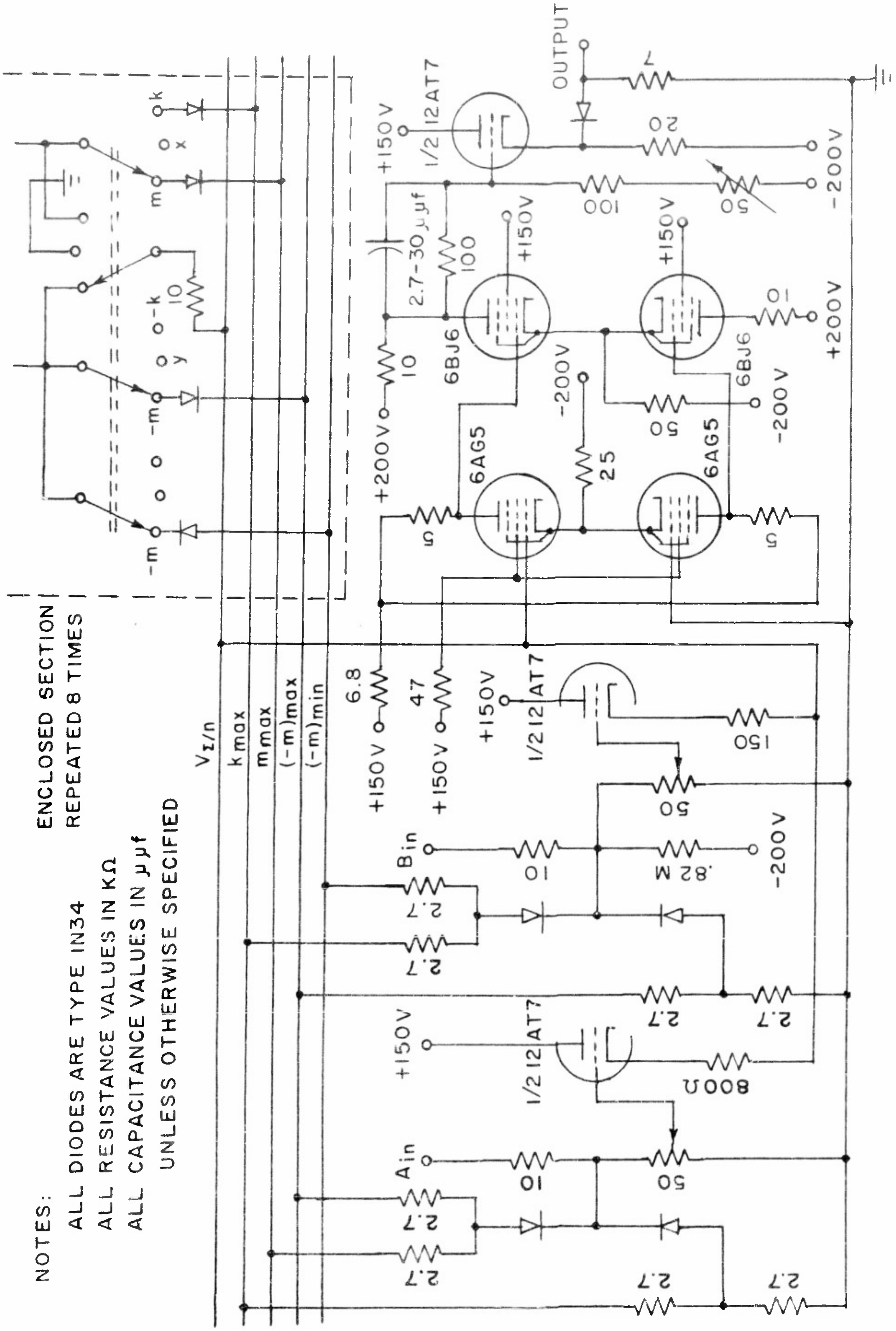
NOTE: ALL RESISTANCE VALUES IN KΩ AND ALL CAPACITANCE VALUES IN μμf UNLESS OTHERWISE SPECIFIED.

FIG. 17. PROTOTYPE MATCHED FILTER FOR I-F SECTION.



NOTE: ALL RESISTANCE VALUES IN K Ω AND ALL CAPACITANCE VALUES IN μμf UNLESS OTHERWISE SPECIFIED

FIG. 18. REVISED SCHEMATIC OF PULSE-TRAIN CORRELATOR (FIRST HALF).



NOTES:
ALL DIODES ARE TYPE IN34
ALL RESISTANCE VALUES IN KΩ
ALL CAPACITANCE VALUES IN μμf
UNLESS OTHERWISE SPECIFIED

ENCLOSED SECTION
REPEATED 8 TIMES

FIG. 19. REVISED SCHEMATIC OF PULSE-TRAIN CORRELATOR (SECOND HALF).

b. Bibliography

1. Harrington, J. V. "An Analysis of the Detection of Repeated Signals in Noise by Binary Integration", Lincoln Laboratory, M.I.T., Technical Report No. 13, (14 August 1952)

2. Rice, S. O. "Mathematical Analysis of Random Noise", Bell Telephone System Technical Publication, Monograph B - 1589. Originally published in B.S.T.J., Vol. 23, pp 282-332 (July 1944) and Vol. 24, pp 46-156 (January 1945)

3. Dancoff, S. "On Signals Imbedded in Noise", Control Systems Laboratory, Univ. of Ill., Contract DA-11-022-ORD-174, Report No. 2 (May 1952)

4. Middleton, D. "Statistical Criteria for the Detection of Pulsed Carriers in Noise", AFCRC Report E5091 (November 1952)

5. Pierce, J. R., and Hopper, A. L. "Nonsynchronous Time Division with Holding and with Random Sampling", Proc. I.R.E., Vol. 40, No. 9, (September 1952) pp 1079-1088

6. Carlson, A. W. "A Transistor Flip-flop with Two Stable, Non-Saturated States", unpublished memorandum (3 December 1952)

7. Forrester, J. W. "Designs and Tests of Electronic Circuits for Operating Safety Margins", Digital Computer Lab., M.I.T., Memorandum M-1828 (January 27, 1953)

8. Daggett, W. L., and Rich, E. S. "Diagnostic Problems and Marginal Checking in the Whirlwind I Computer", Digital Computer Lab., M.I.T., Engineering Note E-536 (March 26, 1953)

9. Boyd, H. "Final Specifications of the High-speed Flip-flop", Digital Computer Lab., M.I.T., Engineering Note E-543 (March 12, 1953)